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October 1980

EXPERIMENTAL STUDY OF SES BOW SLAMMING IN REGULAR WAVES

by

Gerard Fridsma and Walter E. Klosinski

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Experimental measurement of shear force and bending moment of a segmented SES model operating in regular waves in the off-cushion mode. Detailed presentation of experimental results intended for correlation with computer simulation, in both digital and graphical form are included. Results are discussed and it is concluded that the hydrodynamic effects are dominated by structural response of the model. A more direct experimental method of validating the theory is recommended.

STEVENS INSTITUTE OF TECHNOLOGY
DAVIDSON LABORATORY
CASTLE POINT STATION
HOBOKEN, NEW JERSEY

Report 2106
October 1980

EXPERIMENTAL STUDY OF SES BOW SLAMMING IN REGULAR WAVES

by

Gerard Fridsma and Walter E. Klosinski

Prepared for
Surface Effect Ships Project Office
under
Contract N00014-79-C-0914
(DL Project 4768/073)

Approved: P. Ward Brown

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Marine Craft Development
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INTRODUCTION

Operation of SES craft in the off-cushion mode at low speed is expected to lead to bow-slamming. Hullborne operation of SES may be necessitated by considerations of low-speed range, by large sea states, or by loss of cushion power. Studies by the SES Project Office of the structural loads arising in hullborne operation have lead to the conclusion that the slamming loads due to the impact of the bow ramp with oncoming waves are a major factor in the structural design of SES.

A theory for predicting the loads due to SES bow ramp slamming has been developed by Kaplan and Malakhoff[1], and provides for the calculation of loads if the craft motions and oncoming wave elevations are known. In order to validate this theory an experimental program was designed by the SES Project Office. A relatively stiff model of an SES, 12 feet in length with a length-beam ratio of 5, was built at the David W. Taylor Naval Ship Research and Development Center (DWTNSRDC). The bow module forward of the wet deck and between the sidewalls, extending over 23% of the length, was independently supported on load cells so that the bending moment and shear force due to slamming could be measured; this arrangement is sketched on Figure 1. After construction, the model was dynamically calibrated to determine its mode shapes and fundamental bending frequency, which was found to be approximately 10 Hz.

This instrumented model was delivered to Davidson Laboratory for testing in regular waves and in the off-cushion mode. The process of validation required the use of high-quality regular waves and since the ability to generate such waves had been demonstrated[2], the Davidson Laboratory's Tank 3 was selected as an ideal facility for this investigation. Testing took place during December 1979 and was witnessed by representatives of the SES Project Office and Hydromechanics, Inc.

MODEL

Major Components

The SES model supplied by DWTNSRDC consisted of a centerbody, port and starboard sidewalls, and a bow module attached to the centerbody by load cells. A sketch of the model, having a length-beam ratio of 5 (L/B = 5), is included on Figure 1 and photographs of the model ready for test are shown on Figure 6.

The centerbody, 25.75 inches wide by 109.75 inches long by 3.82 inches deep, was constructed of longitudinal and lateral aluminum channels with a 0.06 inch sheet-aluminum wet deck. To increase the longitudinal stiffness, an additional 8 inch deep "L" section, 84.38 inches long, had been attached to the body box on the outboard edges.

The port and starboard sidewalls, 3.00 inches wide by 143.25 inches long by 10.2 inches deep, consisted of wood and foam filled hulls covered with fiberglass and epoxy resin. These were attached to the centerbody on 0.06 inch spacers to allow room for the bow module to deflect without touching the sidewalls. A strut, 3/8 inch in diameter, was mounted at the stem of the sidewalls to maintain their separation.

A bow module, 33.10 inches in length was an extension of the centerbody and of similar construction, see Figures 1 and 2. This separate module was attached to the centerbody through port and starboard load cells (block gages) that were strain gaged to measure the horizontal and vertical force, and the torsional moment. The load cell is shown in Figure 3. For the purpose of these tests, the load cells were mounted in the model so that the bending moment due to the bow module was sensed and measured by the torsional moment gages. It was found that the bow module was torsionally weak and therefore, to minimize induced cross-coupling in the load cells, steel tension wires were stretched diagonally between opposite corners. The underside of the bow-module wet-deck and ramp was painted with a 2 inch square grid to facilitate the interpretation of underwater high-speed motion picture photographs.

Model Mass Distribution

The L/B = 5 SES model was ballasted to achieve the longitudinal distribution of mass shown in Appendix A. This was the mass distribution used during the structural response experiments which were supervised by Rohr Marine, Inc. The ballasting includes concentrated weights of 11.94, 31.30, and 36.00 lb located at 11.75, 62.75, and 77.50 inches respectively forward of the transom; and about 10 lb in distributed weight. This 10 lb distributed load was made up of lucite decking across the centerbody and bow-modules, of instrumentation, and of fifteen 0.3 lb lead weights taped within the central portion (mid 30%) of the body box. When weighted and balanced, the actual L/B = 5 SES model as tested came to 234.6 lb with an LCG of 67.5 inches forward of the transom which is within 0.8 lb and 0.1 inches of the Rohr values. The heave staff and pitch pivots were located at 62.75 inches forward of the transom and their weights are included as part of the 31.30 lb concentrated load at this location.

APPARATUS AND INSTRUMENTATION

Model Instrumentation

The L/B = 5 SES model was equipped with load cells, a bow accelerometer, a trim inclinometer, and a bow deflection indicator.

A sketch of the DWTNSRDC load cell is included on Figure 3. In order to calibrate these cells as installed in the model using a dead-weighting system the centerbody and bow-module were turned upside down and mounted securely to a surface plate as shown in Figure 4. Threaded rods inserted in the existing holes in the side girders provided the means for applying combinations of vertical load and pitch bending moment in the positive sense. A pulley system was used to apply drag loads. The port and starboard load cells were both intended to measure the lift, drag, and pitching moment of the bow-module. The load cells were delivered without either electrical connections or schematics. Consequently the six strain gage bridges were connected to amplifiers as indicated in Figure 5. Shunt resistors were included in the circuits to provide calibration signals of approximately half the full-scale signal. The values of these signals (Cal. Sig.) are given on Figure 5. The details and results of the calibration are given in Appendix B. Of the two

cells, the starboard one generally exhibited less cross-coupling and hysterisis and it is the output from this cell that is reported.

An accelerometer was installed in the bow-module on the longitudinal centerline of the wet deck and bow ramp whose position is 59.90 inches forward and 3.78 inches below the pitch axis at zero degrees trim.

A wave wire was mounted on the bow-module at the longitudinal position of the knuckle and 4 inches outboard of the starboard sidewall. The signal from this transducer was calibrated to record the draft of the knuckle relative to the local wave elevation. It should be noted that this local wave elevation may differ from that of the incident wave due to the influence of the model.

A trim inclinometer was fitted in the centerbody, 83 inches forward of the transom, to monitor the static trim.

A bow deflection indicator was mounted on the starboard sidewall, 1.5 inches aft of the leading edge of the bow-module. This transducer was used to record the motion of the bow-module during an impact relative to the rigid sidewall.

Facility Instrumentation

A standard free-to-heave apparatus was coupled to the model through a pivot box whose pitch axis was located 62.75 inches forward of the transom and 3.86 inches above the wet-deck. While allowing the model heave and pitch freedom, the apparatus fixed the craft in roll, sway, and yaw. Heave and pitch transducers were provided to measure the motions of the pitch axis. A moving wave wire mounted abreast of the bow-module knuckle and 4 feet off the port sidewall measured the wave profile. A photograph of the experimental setup is included as Figure 6.

The thirteen transducer signals were relayed through overhead cables to the data station on shore where they were recorded on analog magnetic tape and on a direct writing oscillograph. The load and acceleration signals were not filtered, (the frequency response of the electronic system is flat to 300 Hz) however, the motion and wave elevation signals were low-pass filtered to 40 Hz. In order to monitor the results at tank side, a peak-trough analysis was carried out by the on-line PDP-8e computer and some of these results were given to the observers.

A camera carriage was mounted ahead of and to port of the model bow in

order to observe the model behavior on a remote TV monitor. All runs were video-taped (color) and are on file at the Davidson Laboratory. Color underwater motion pictures were taken of the wet deck wetting for the zero speed conditions. These were taken at 125 frames/second at the 150 foot station in the tank. The view looking directly up at the bow module was obtained with the aid of an underwater mirror on the bottom of the tank. Part of this setup can be seen in Figure 6.

Wavemaker

The Tank 3 plunger type wavemaker, located at the far end of the tank, was used to generate the required regular waves. Waves having nominal heights of 5 and 6 inches with periods of 1.0, 1.4, and 1.8 seconds were used. The actual wave height was computed from the wave rms (2.83 rms). A harmonic analysis was carried out for the four waves used in this study. The results are shown in the following table of amplitudes at frequency multiples of the fundamental of 0.5, 1, 2, and 3. The component amplitudes have been normalized by 1.41 rms.

HARMONIC ANALYSIS OF WAVE PROFILE

		Relative Amplitude			
Wave Period seconds	Wave Height inches	0.5	1.0	2.0	3.0
1.31	5.67	0.021	0.977	0.059	0.014
1.39	5.15	0.020	0.968	0.051	0.004
1.41	6.24	0.010	0.990	0.077	0.023
1.80	4.82	0.008	0.973	0.046	0.021

It may be seen that very little energy appears at other than the fundamental frequency and that therefore the generated waves are almost pure sine waves. One of the observed wave elevation time histories (1.41 second period by 6.22 inch height) is compared with its Fourier representation on Figure 7.

DATA REDUCTION

Calibrations of the instrumentation were made by applying known loads and moments to the load cells, gravity multiples to the accelerometer, and known displacements to the motion, wave, and bow deflection transducers. During calibration, the outputs from the transducers were fed to the PDP-8e computer. All calibrations were linear and straight lines were fitted to these

data by the least-squares technique. Calibration signals based on the computer rates were used for all data channels.

During the tests, all data was recorded on the analog tape recorder and time history records were generated on the ultra-violet light oscillograph. Tank-side output was obtained from the PDP-8e computer using a peak-trough analysis. Following the tests, all the data was digitized at 250 Hz, converted to engineering units, and transferred to CDC-compatible digital magnetic tape.

TEST PROGRAM AND PROCEDURE

The tests were conducted free-to-trim and heave at constant speeds of 0 and 2.7 fps. Nominal regular wave heights of 5 and 6 inches were used with wave periods of 1.3, 1.4, and 1.8 seconds in order to produce a combination of wave and model motions calculated to result in significant bow slamming. The actual run parameters are shown in the following table:

RUN PARAMETERS

RUN No.	Model Speed fps	Wave Period sec.	Wave Length ft.	Wave Height in.	Encounter Period sec.
21	0	1.31	8.75	5.67	1.31
22	0	1.39	9.91	5.15	1.39
23	0	1.41	10.14	6.24	1.41
25	2.7	1.39	9.91	5.15	1.00
24	2.7	1.41	10.14	6.24	1.03
26	2.7	1.80	16.14	4.82	1.39

The procedure followed for the tests was to wait for calm water, place calibration signals and zeros on the analog tape, and proceed to start the waves. After the first 5 or 6 waves passed the model, either at 0 or 2.7 fps, the motions and slamming behavior would become periodic. Data was then taken for about 10 wave cycles. A wave suppressor was activated after each run for a partial traverse of the tow tank. This device re-distributes the residual wave energy to higher frequencies where it is rapidly dissipated.

The zero speed conditions were repeated in another section of the tank for the purpose of taking underwater motion pictures of the bow ramp wetting. A strobe unit, fired at the moment the computer was pulsed to receive data, synchronized the movie with the data time history. Video tape recordings were made of all runs.

RESULTS

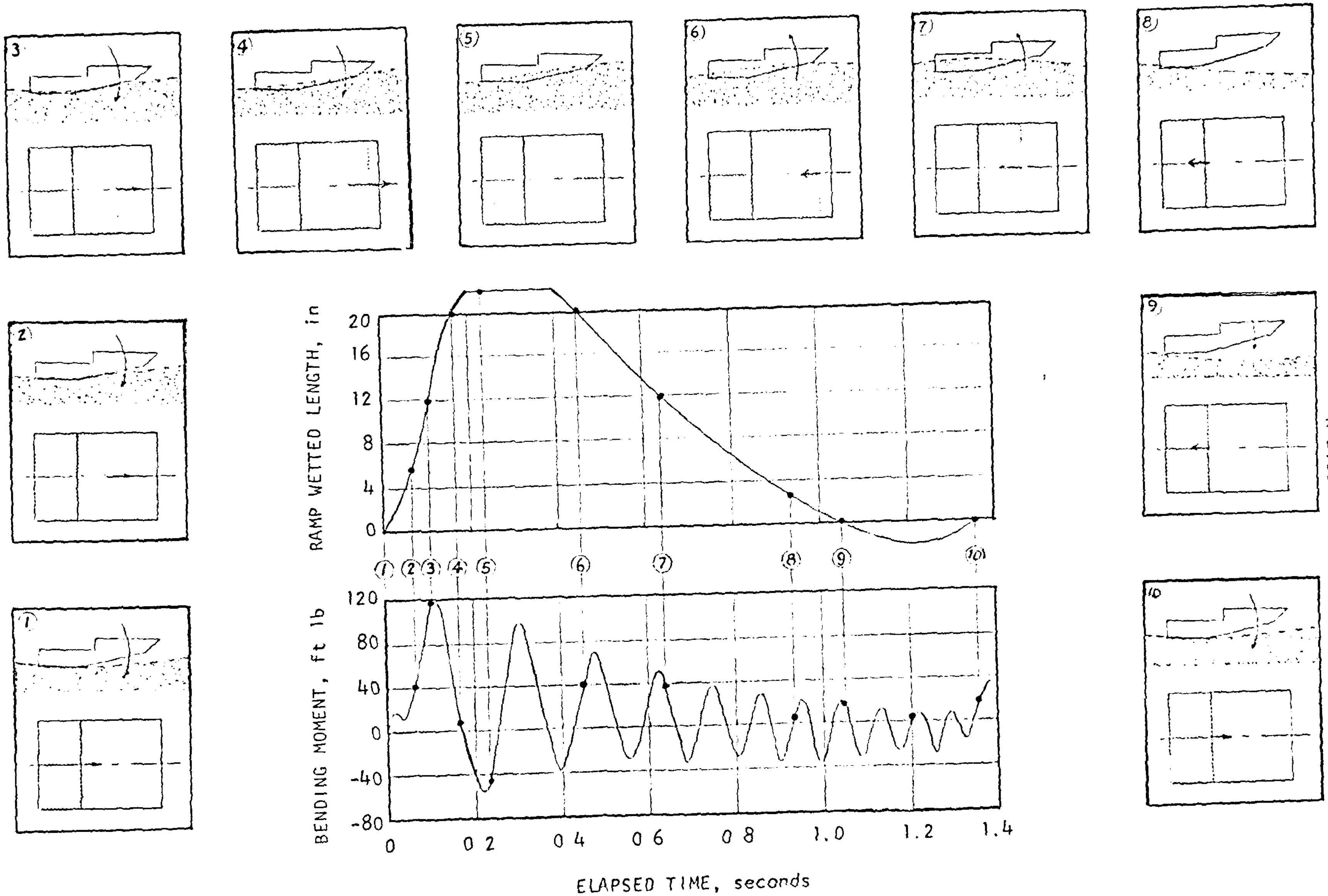
The results of these slamming experiments consist of time histories of the craft pitch and heave motions; the shear force, bending moment and acceleration of the bow-module, and the wave elevation. These time histories have been recorded on an IBM compatible magnetic tape supplied to the SES Project Office. The tape and associated line-printer listing include the digital time histories of the six runs, at 4 millisecond intervals (scan rate of 250 Hz). Each run contains the pitch, heave, relative draft, wave height, bow shear, bow bending moment, bow acceleration, and bow deflection signals, in that order, in engineering units. The tape itself has six files, one for each run, which is written 80 characters per record and 60 records per block. There are 9 tracks on the tape packed 1600 bits/inch. Odd parity, unlabled, EBCDIC coding is used.

The digital form of the time histories is intended to facilitate comparison with theory. In addition, graphical presentations of the time histories of Runs 21 to 26 are included on Figures 9 to 14 showing the lift, pitching moment, pitch, heave, relative draft (of the knuckle), bow acceleration, bow deflection and wave elevation.

In addition to the digital data obtained, the underwater movies provided data on the position of the waterline intersection with the bow-module. With a movie film analyzer, a frame by frame time history of the waterline intersection with the bow ramp was obtained. Using the over-exposed frame of film (illuminated by the setting off of an electronic flash which simultaneously injected a pulse onto the time base record) to synchronize the movie and other time histories, the ramp wetted length as a function of time could be determined and compared with the motion and pitch moment data.

DISCUSSION

In order to provide a framework for this discussion, the time history of one slam event will be described with the aid of Figure 8, which is also bound alongside this account. This composite display shows the variation of ramp wetted length and bow-module pitching moment during one slam event at zero speed, in a wave 5 inches high with a period of 1.4 seconds. Surrounding these time histories are scaled sketches of the bow-module (without the centerbody) and the water surface at a sequence of instants during the slam. The numbers



TYPICAL TIME HISTORY OF BOW SLAM EVENT, ZERO FORWARD SPEED
WAVE ENCOUNTER PERIOD 1.4 SECONDS

in the upper left hand corner of the pictures correspond to the numbers on the time history. The position and movement of the wetted portion of the bow module is represented by the shaded portion in the lower half of the picture where the knuckle is displayed as a solid line. The upper half of the picture shows in profile the position and motion direction of the bow module in the wave. Starting at time zero with Picture 1 the following sequence of events may be noted.

Picture 1: The impact begins at time zero as the knuckle reaches the water surface. The bow is moving downward at its maximum angular velocity and at this instant the bow-module wet-deck has a slight bow-down trim of about 1°.

Picture 3: The penetration of the water surface by the bow-module continues and the pitching moment reaches its first maximum. The ramp is wet over 70% of its length and the leading-edge of the wetted area (the stagnation line) is advancing at its maximum velocity of 17 fps. It may be noted that the craft velocity is zero and the wave celerity is 7 fps.

Picture 5: The bow-module is completely immersed at its maximum bow-down altitude and the knuckle is at the steepest part of the wave midway up the flank. The pitching moment oscillation has completed one cycle at a frequency of 5 Hz.

Picture 6: The angular velocity of the bow-module on its elastic supports, reverses direction as the wave crest reaches the top of the ramp, so that the module moves up and the stagnation line begins to retreat toward the knuckle.

Picture 7: At this instant the knuckle attains its maximum immersion with the wave crest at the knuckle. The trim of the bow-module wet-deck is zero. The pitching moment response has completed 3.5 cycles.

Picture 8: The bow reaches its maximum trim just as the waterline intersection approaches the knuckle. The relative draft time history indicates the knuckle is already out of the water and directly opposite the receding flank of the wave.

Picture 9: The waterline intersection has reached the knuckle by this time and the bow has once more reversed its direction, heading back toward the wave surface. The relative draft of the knuckle is a minimum

at this point being almost 2" above the water. The rate of oscillation of the pitching response has speeded up to 10 Hz.

Picture 10: The process is about to start for the second cycle (see Picture 1). Prior to this the waterline intersection moved just aft of the knuckle and then began its forward movement. During this period of one wave encounter, the pitch moment response has gone through 11 oscillations.

This sequence of events is typical of the slam events observed during these experiments. Generally the period of the response coincided with the period of encounter with the wave, as suggested by Figure 8. However in two cases, Run 21 at zero speed and Run 26 at 2.7 fps, (see Page 6) the period of response was equal to twice the ecounter period. This feature of the impact response will be demonstrated later, although no explanation for this non-linear behavior is offered.

Also typical of the pitching moment response and of the bow-module deflection, to be discussed later, is the fact that during the impact the frequency of response increases from 5 Hz to 10 Hz. This type of behavior could be explained by the non-linear impact force that this experiment was designed to validate. Assuming that the bow-module on the elastic load cells can be represented by a damped single degree of freedom elastic system, the vertical motion, z, of the bow-module would be given by:

$$m\ddot{z} + c\dot{z} + kz = F_i \tag{1}$$

where F_i is the hydrodynamic impact force. If this exciting force were a constant amplitude harmonic force, the system would eventually respond at the frequency of the exciting force, once the initial transient response had died out. During impact, however, the exciting force postulated by Kaplan and Malakhoff is a non-linear function of acceleration, velocity, and displacement, therefore the response equation becomes:

$$m\ddot{z} + c\dot{z} + kz = F_i(\ddot{z}, \dot{z}, z) \tag{2}$$

This equation could explain qualitatively the type of response observed, unless it is argued that the response is entirely governed by the left-hand-side of Equation 2, i.e. the structural characteristics of the model, in which case it must be concluded that the experiment is not suitable for

validating the theoretical prediction.

Having described the typical bow slam event the individual runs will be discussed in detail. The results of the three runs at zero speed, Runs 21, 22, and 23, are presented on Figures 9, 10, and 11; similarly the results of Runs 25, 24, and 26 at 2.7 fps are shown on Figure 12, 13, and 14. Each of these figures consist of three sheets, each sheet consisting of a number of time histories as indicated in the following listing for Run 21:

Figure 9.1	Wave elevation Shear at rear of bow-module Bending moment at rear of bow module
Figure 9.2	Wave elevation Pitch angle of centerbody Heave motion of tow point
Figure 9.3	Wave elevation Relative draft at knuckle Bow-module acceleration Bow-module displacement

The wave elevation time history is repeated at the top of each figure to provide a reference. It should be noted that this record is not of the incident wave but of the wave elevation abreast of the knuckle and has been contaminated by the waves generated by the model. The base of these time histories has been normalized by the period of encounter with the waves and therefore shows the time in units of encounter period.

The results obtained in Run 22 at zero speed, shown on Figure 10, are fairly typical. On Figure 10.1, the results obtained in three consecutive wave periods have been superimposed, and it may be seem that the slam event has a fundamental period equal to the period of encounter, with remarkably little variation from wave to wave. Superimposed on this period is the ringing of the bow module on its elastic foundation. This dominance of the response by the structural characteristics of the model is typical of all the data obtained. The pitch and heave motions of the craft shown on Figure 10.2 are repeated in each wave cycle as might be expected. For all the runs at zero speed the pitch and heave at the tow-point are in phase, lagging the wave elevation at the knuckle by about 90°. Turning to Figure 10.3 it may be seen that the knuckle draft at zero speed follows the wave at the knuckle and leads it by approximately 36°. The trace of the

bow-module deflection at the bottom of Figure 10.3 is remarkably similar to the bending moment at the bottom of Figure 10.1--in fact, they can be overlaid to show the deflection lags the moment by 8°. The gross motion of the stem of the bow-module may be noted, amounting to 0.4 inches peak to peak.

Run 23 was almost the same as Run 22, except that the wave height was increased from 5.15 to 6.24 inches and similar results were obtained as shown as shown on Figure 11.

The shear and bending moment response in Run 21 by contrast, at the longer period of 1.31 seconds, exhibited a fundamental period equal to twice the encounter period. As may be seen on Figure 9.1 the response to every other wave was remarkably repetitive. The significance of this non-linear behavior is perhaps more relevant to the response of elastic structures to regular waves than the validation of impact theory. It was noted again at the forward speed of 2.7 fps as shown on Figure 14.1.

When the model is given a forward speed of 2.7 fps (a Froude Number of 0.14 based on overall length) the motion response in the shorter 10 foot waves, Figures 12.2 and 13.2, becomes markedly non-sinusoidal, and the heave becomes almost aperiodic. When the wave length is increased to 16 feet, Figure 14.2 shows that the periodic sinusoidal response is recovered.

The fact that the structural response to slamming increases in frequency following the initial impact has already been mentioned. What is even more remarkable is that the initial frequency of vibration is always 5.1 Hz and the final frequency is alsways 12.2 Hz. Over the limited range of this data, this observation holds for model speeds of zero and 2.7 fps, wave lengths from 9 to 16 feet and encounter periods of 1.0 to 1.4 seconds. It might be concluded that the structural response of the model dominates and masks the hydrodynamic forcing function.

In any event it appears that the structural response of the model has a characteristic period of the order of 100 milliseconds. In the full-scale experiments with the XR-1D reported by Russell the rise time of some of the impacts was shorter than 10 milliseconds.[3] Rise times of this order cannot possibly be followed by an elastic system with a time constant that is an order of magnitude greater. In addition it should

be remarked that a model structure needs to have a still shorter time constant since on sub-scale models the time is reduced by the square-root of the scale ratio.

CONCLUDING REMARKS

The foregoing material provides ample data and documentation designed to validate the theoretical prediction of the elastic response of an SES model to hydrodynamic impact. Unfortunately it appears that the structural behavior of the model completely masks the hydrodynamic forcing function, and it is the force which has been predicted[1] and which it is desirable to validate.

A preliminary attempt to validate the predictive method using the results of Run 22 was made by Kaplan and Jiang.[4] These authors observe that in the modal response of the model as determined by the Structural Dynamics Research Corporation there was no indication of any resonant natural frequency in bending at 6 Hz, in fact first resonance occurred at 9.5 Hz. However, immediately after hydrodynamic impact the bow-module vibrates at 5.1 Hz, as noted above. The authors observe that because of this discrepancy in the resonant frequencies "some difficulty is to be expected in achieving good correlation results between theory and experiment in the present case for the L/B = 5 craft."[4] Later in this same correlation report it is concluded "In view of the various difficulties experienced in trying to correlate this [Davidson Laboratory L/B = 5] data, and the basic lack of appropriate and accurate structural information on mode shapes and frequencies that are known to be exhibited in the experimental output this particular data does not appear to be fruitful for this purpose."

It certainly seems reasonable to conclude that if in order to validate a hydrodynamic theory it is necessary to undertake an elaborate structural characterization of the model, then the experimental output is indeed not suited to this purpose. It is therefore concluded that in order to validate the hydrodynamic theory of SES slamming it is appropriate to design an experimental technique that is independent of the structural properties of the model.

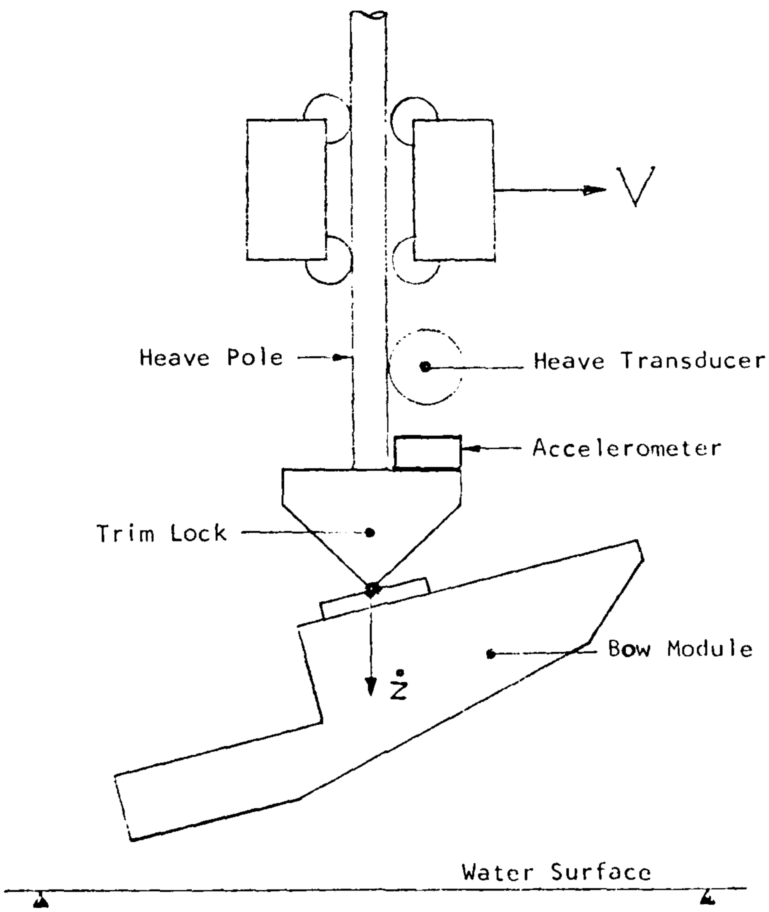
RECOMMENDATION

The difficulties with validating the theoretical prediction of SES impact are due to the presence of structural terms in the response equation, Equation 2 introduced above:

$$m\ddot{z} + c\dot{z} + kz = F_i$$

where F_i is the hydrodynamic impact force to be validated and k and c are the stiffness and damping, respectively, of the structural model. If an experiment is designed in which the stiffness and damping are zero, the observed acceleration will be directly proportional to the impact force.

This can be achieved by a simple impact test, of the kind used to validate seaplane impact theory. The bow-module would be attached to a heave pole at a series of fixed trims, accelerated up to speed, and then dropped on the water at various vertical velocities. Time histories of the ensuing displacement and acceleration would provide direct experimental evidence for comparison with theory. A sketch of the experimental setup is shown below.



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APPENDIX A

DTNSRDC L/B = 5 SES MODEL

LONGITUDINAL MASS DISTRIBUTION

The longitudinal mass distribution of the L/B = 5 model is given below in 24 six-inch-long segments, and is the same as the distribution used when the model structural response was determined by Structural Dynamics Research Corporation. The configuration is with the centerbody stiffeners and concentrated weights of 11.94, 31.30, and 36.00 lb at the respective locations from the transom of 11.75, 62.75, and 77.50 inches. In addition approximately 10 lb of distributed weight is included in these figures to account for decking and wiring.

Segment	Distance from transom to middle of segment, in.	Weight of each segment, lb.
1	3	8.00
2	9	12.01
3	15	9.27
4	21	7 09
5	27	6.85
6	33	6.51
7	39	5.95
8	45	5.85
9	51	5.09
10	57	8.47
11	63	39.02
12	69	9.51
13	75	28.66
14	81	22.44
15	87	5.33
16	93	6.10
17	99	5.73
18	105	8.08
19	111	10.98
20	117	7.11
21	123	4.47
22	129	5.47
23	135	3.29
24	141	4.15

APPENDIX B

LOAD CELL CALIBRATION

The NSRDC load cells shown on Figure 3, both port and starboard, were calibrated in place in the model as shown on Figure 4, after being connected as shown on Figure 5. The full-range calibration loads applied were 250 lb in shear, 365 ft-lb of bending moment, and 45 lb in drag. Since the model was to be tested on straight-course in long-crested head seas, it was assumed that the test loads would be symmetrical about the centerline and the calibration loads were applied similarly.

Both load cells exhibited small amounts of cross-coupling and hysterisis. Since the starboard cell was better in this regard than the port by a factor of three, and there was no provision for summing the outputs, the signal from the starboard cell was recorded during the tests. For the starboard cell, the cross-coupling in terms of the above full-range loads amounted to 0.3% in bending moment due to shear and 3.1% in shear due to bending moment; the effects of drag were negligible. Overall precision of calibration due to cross-coupling and hysterisis was ±1.5 ft-lb in bending and ±1 lb in shear.

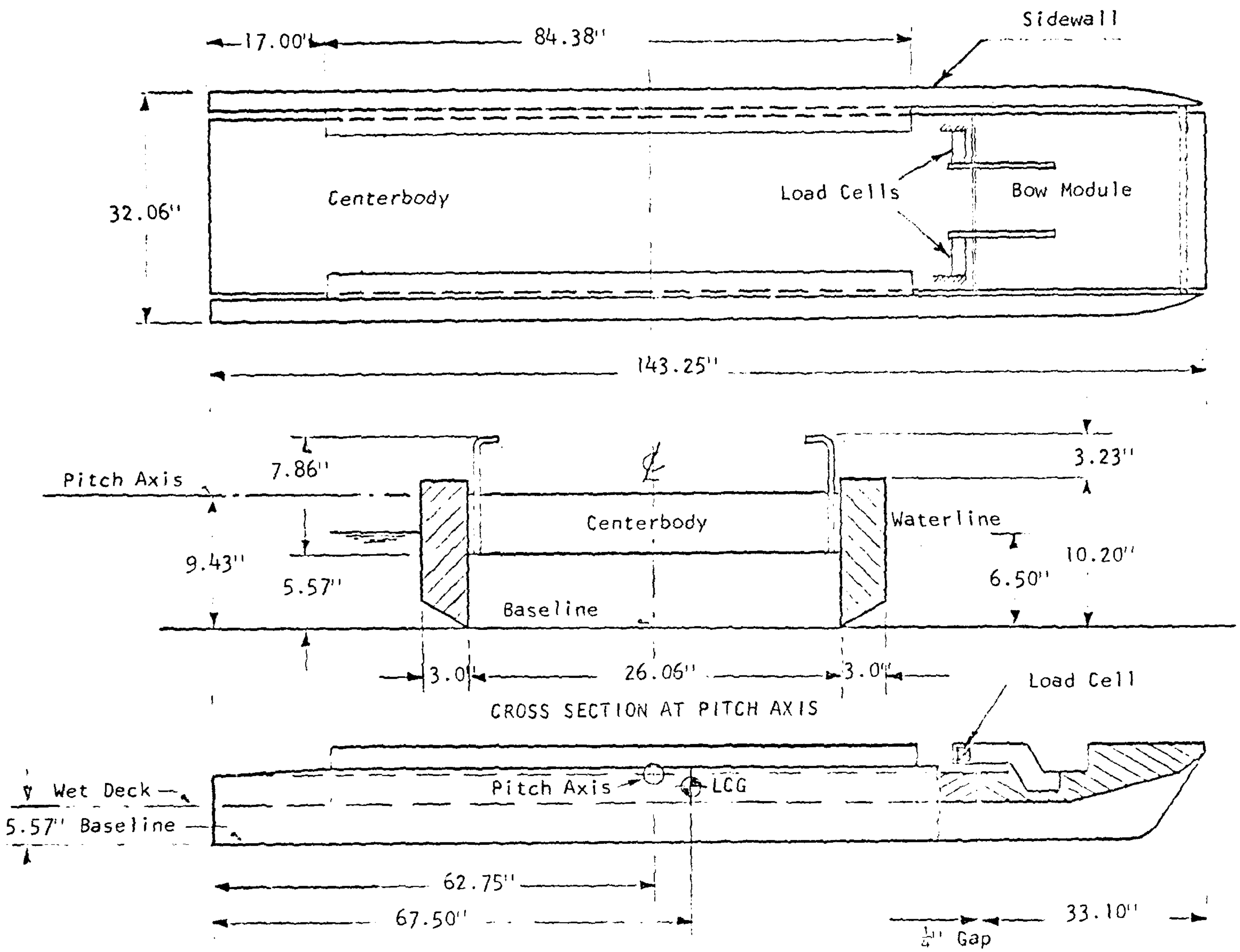


FIGURE 1 PRINCIPLE DIMENSIONS OF THE L/B = 5 SES MODEL

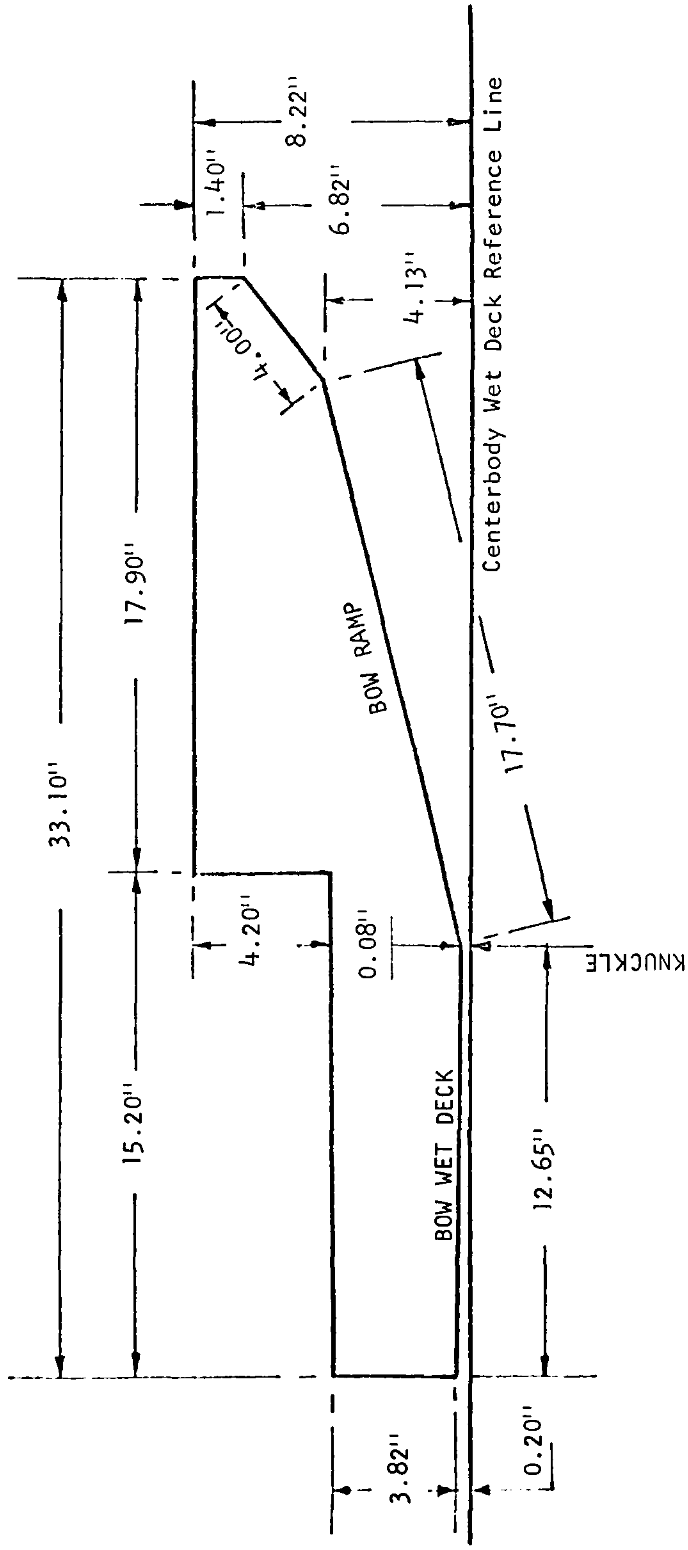


FIGURE 2 BOW MODULE

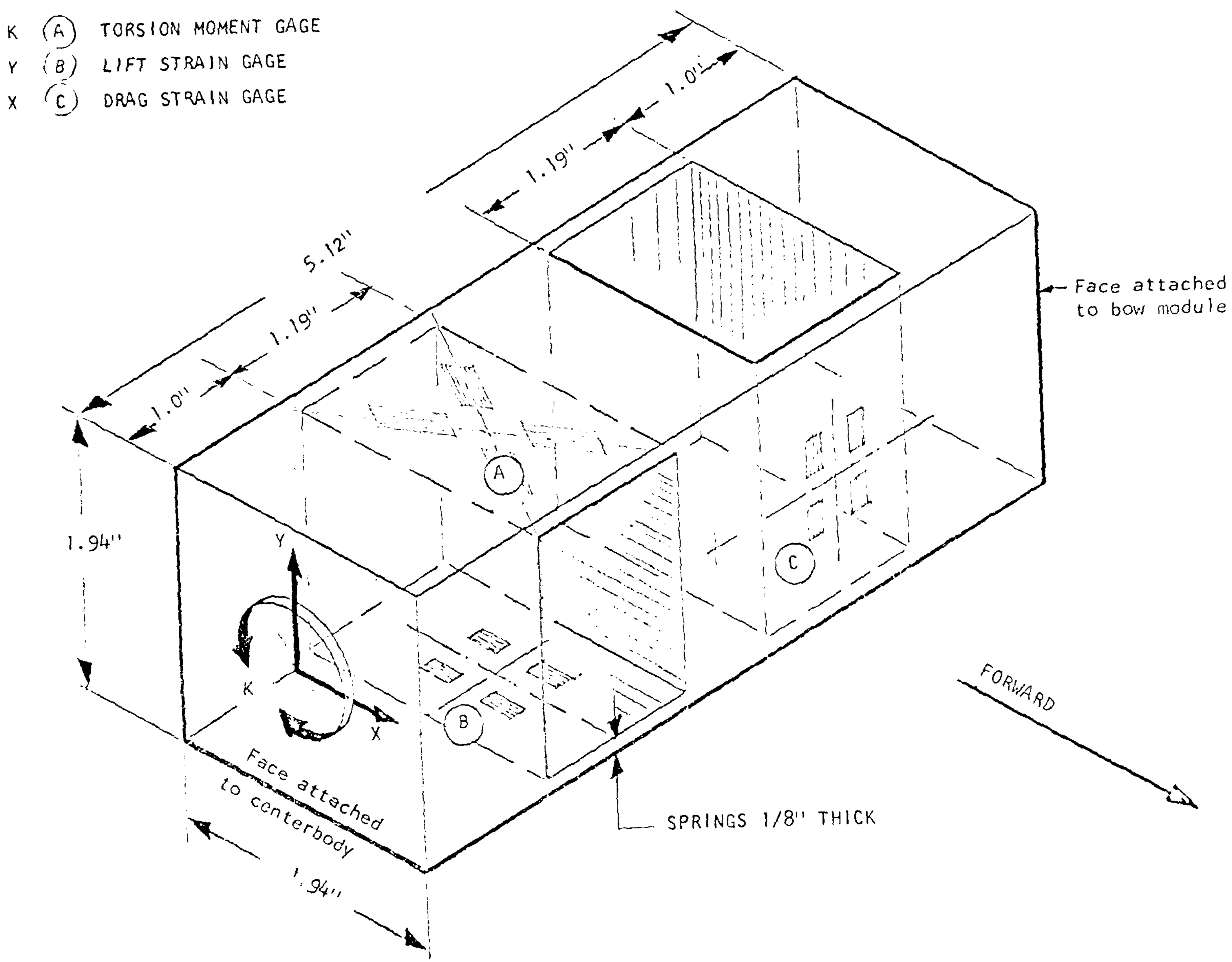


FIGURE 3 SCHEMATIC OF PORT LOAD CELL

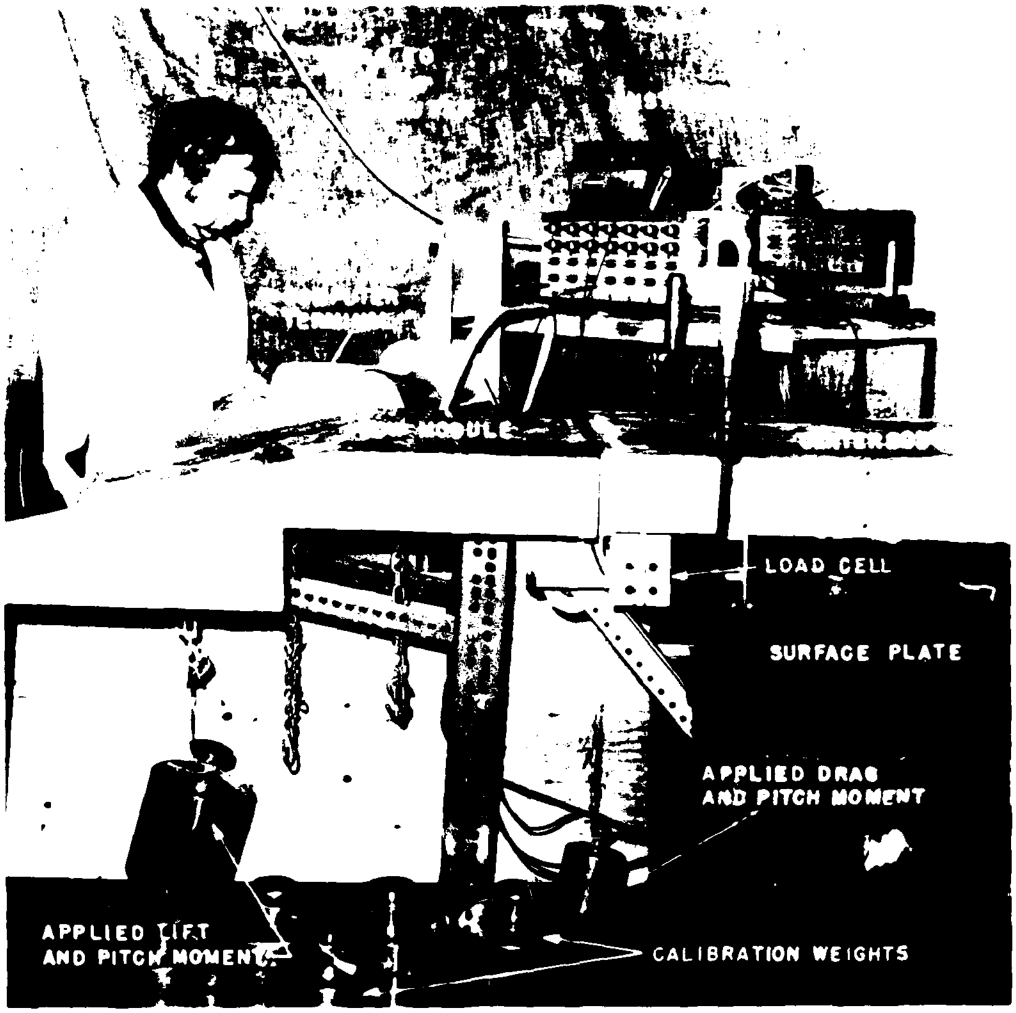


FIGURE 4 LOAD CELL CALIBRATION SETUP

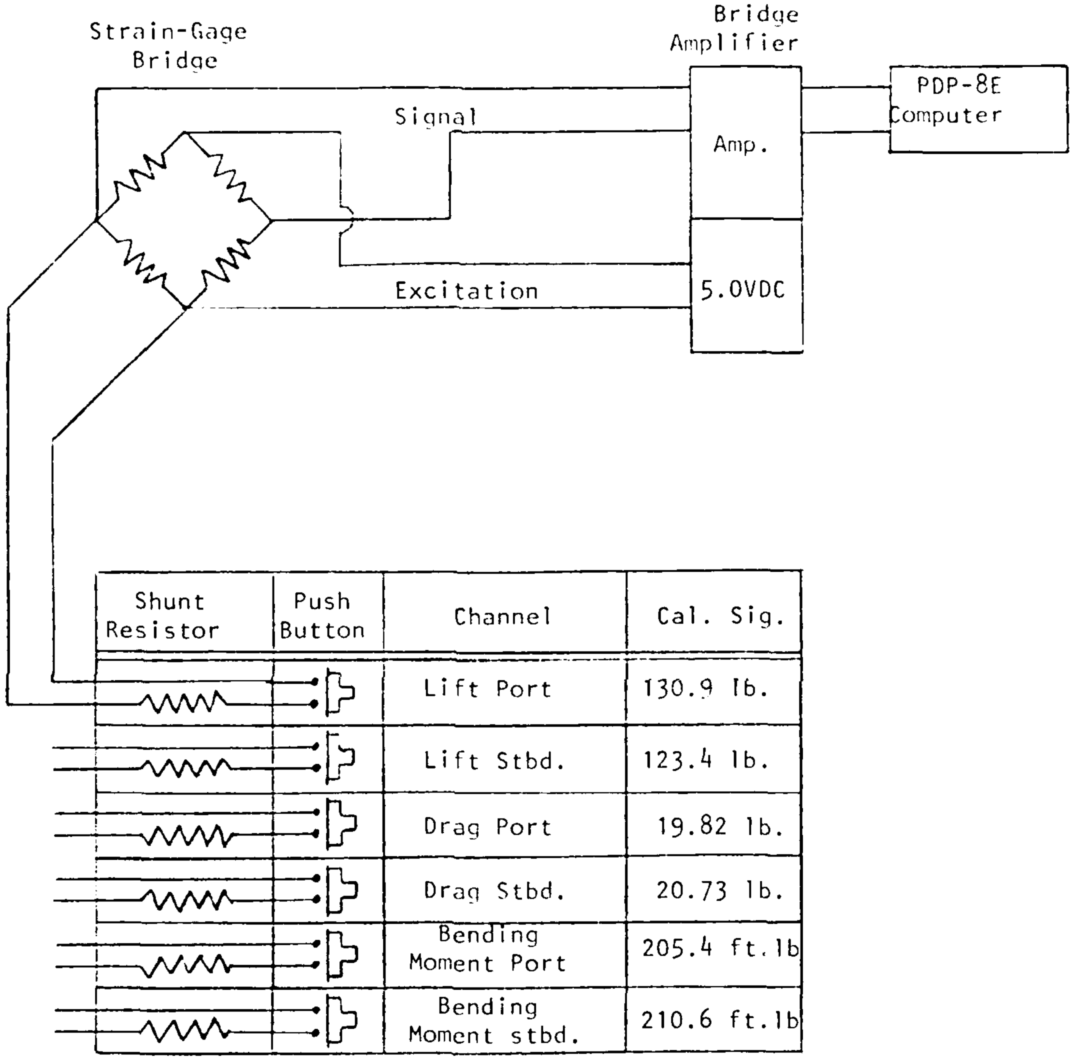
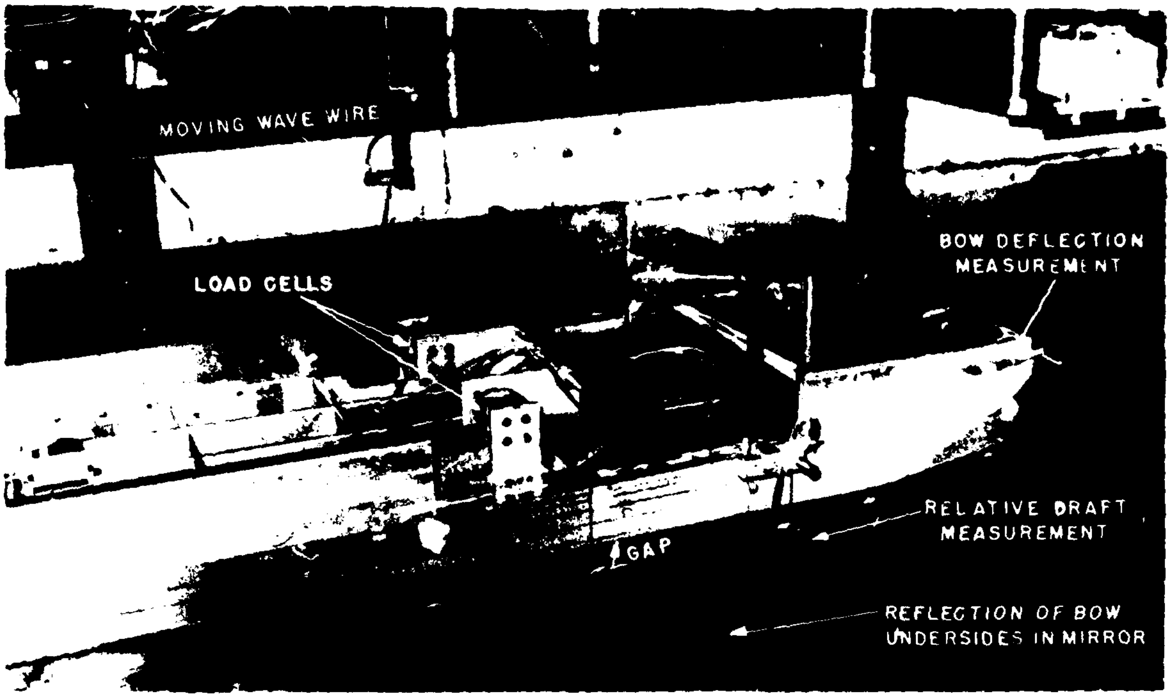


FIGURE 5 STRAIN-GAGE SCHEMATIC



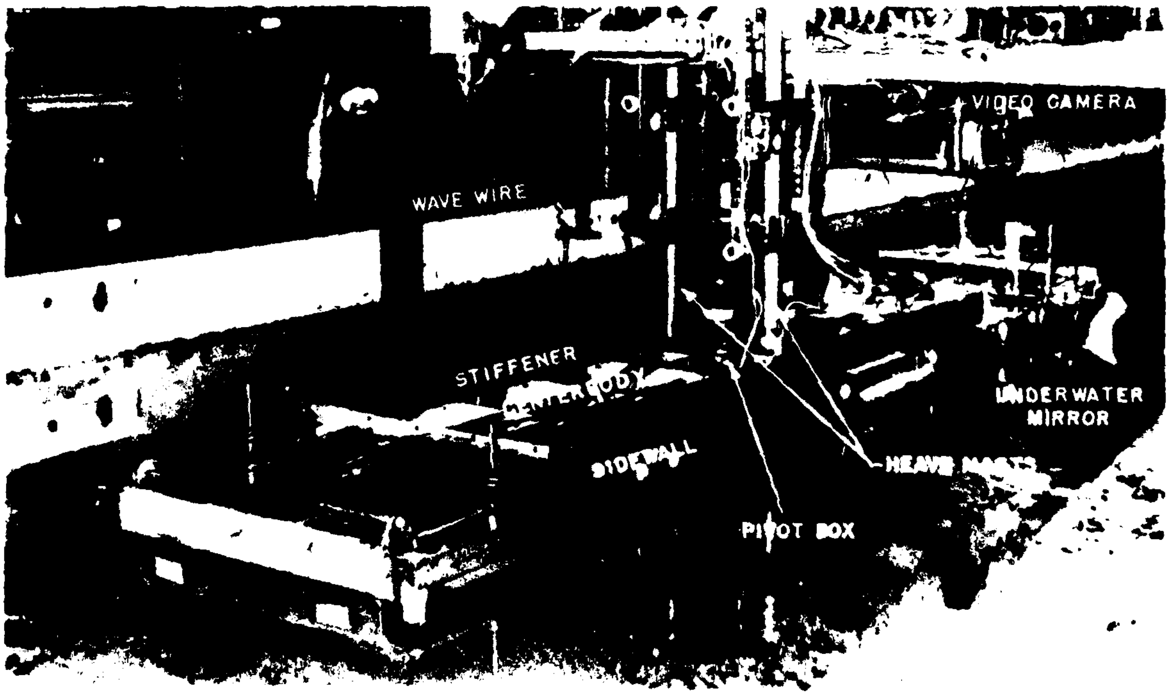


FIGURE 6 MODEL SETUP

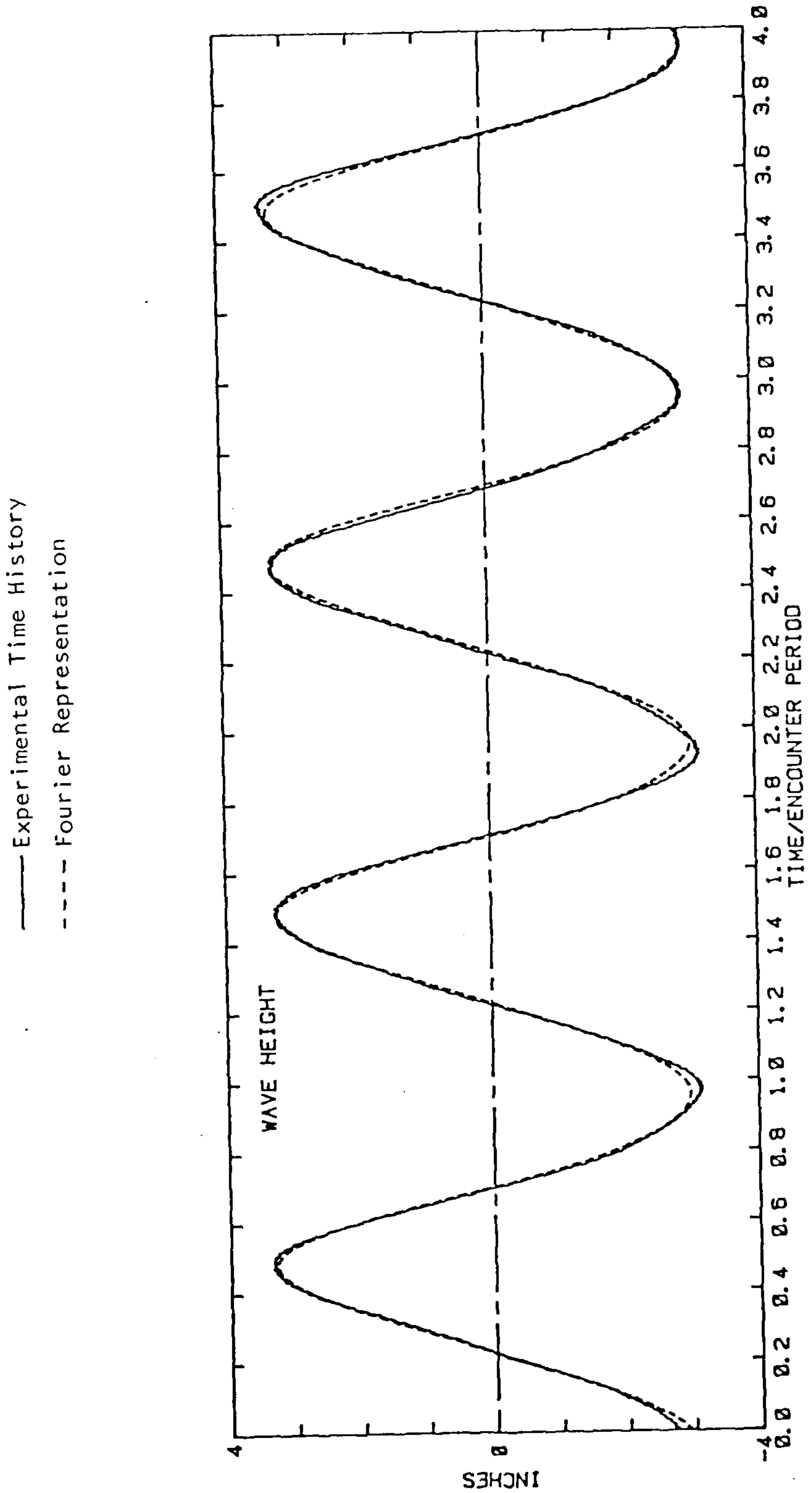


FIGURE 7 WAVE PROFILE COMPARISON(Run 23)

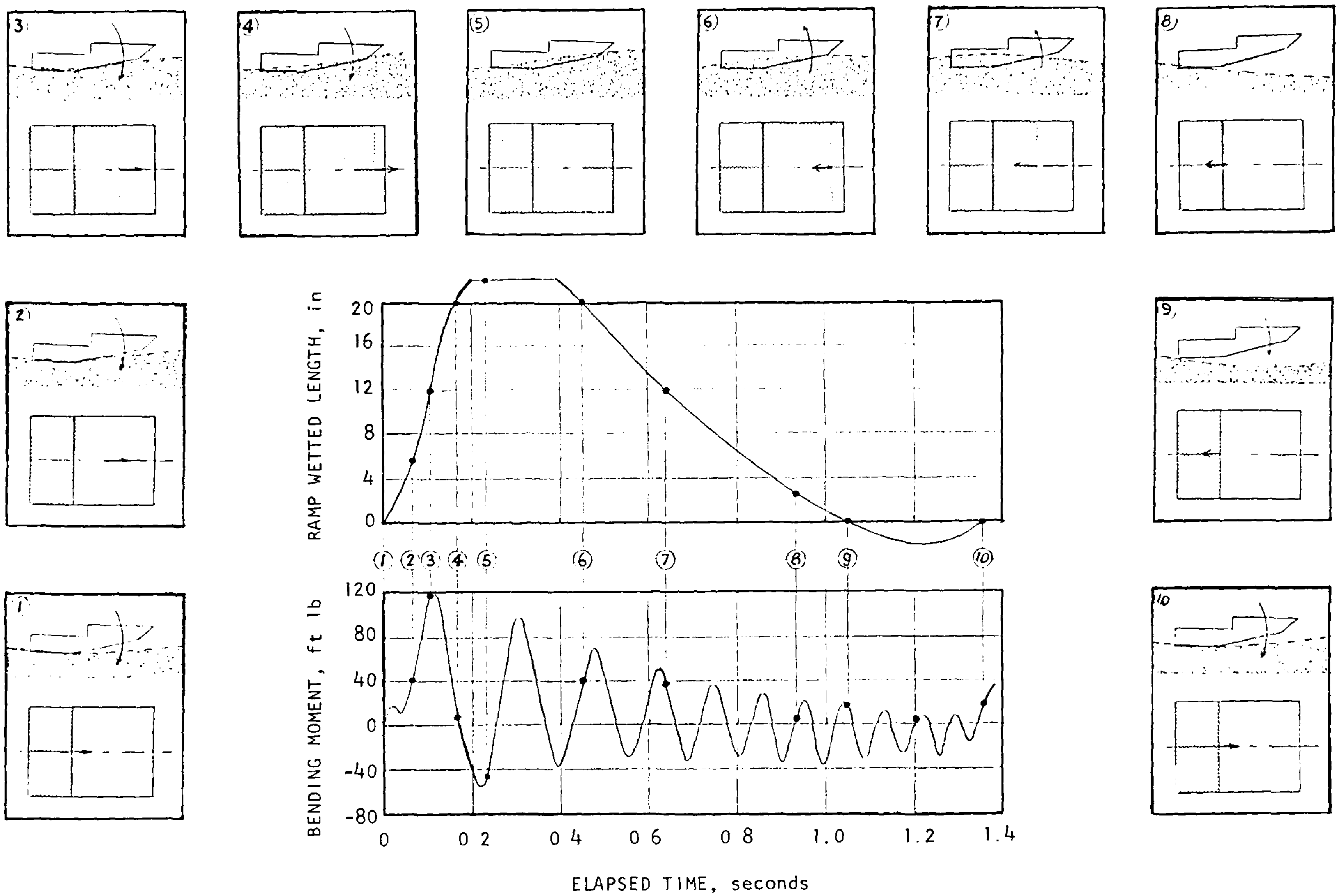


FIGURE 8 TYPICAL TIME HISTORY OF BOW SLAM EVENT, ZERO FORWARD SPEED WAVE ENCOUNTER PERIOD 1.4 SECONDS

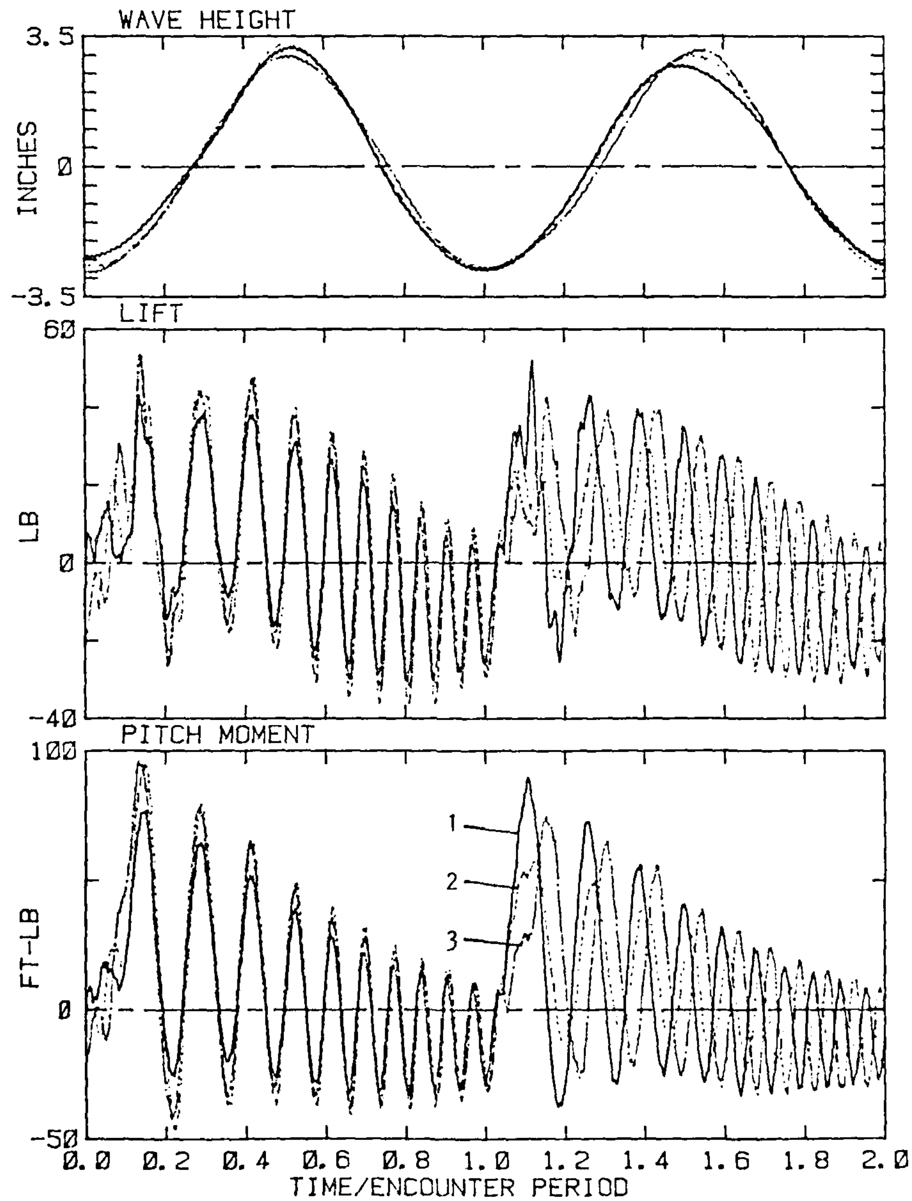


FIGURE 9.1 WAVE ELEVATION, SHEAR AND BENDING MOMENT, RUN 21 MODEL SPEED ZERO, ENCOUNTER PERIOD 1.31 SECONDS, WAVE HEIGHT 5.67 INCHES

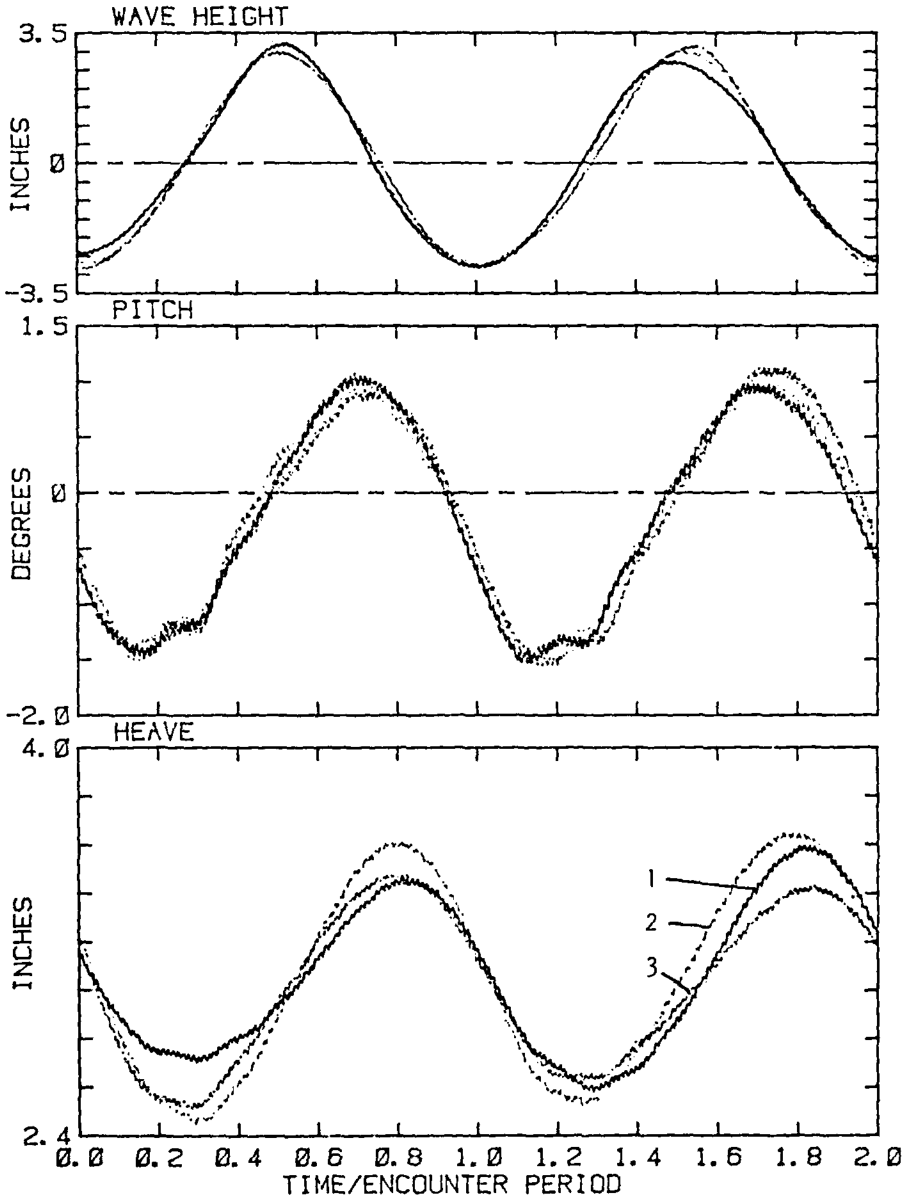


FIGURE 9.2 WAVE ELEVATION, PITCH AND HEAVE, RUN 21, MODEL SPEED ZERO, ENCOUNTER PERIOD 1.31 SECONDS, WAVE HEIGHT 5.67 INCHES

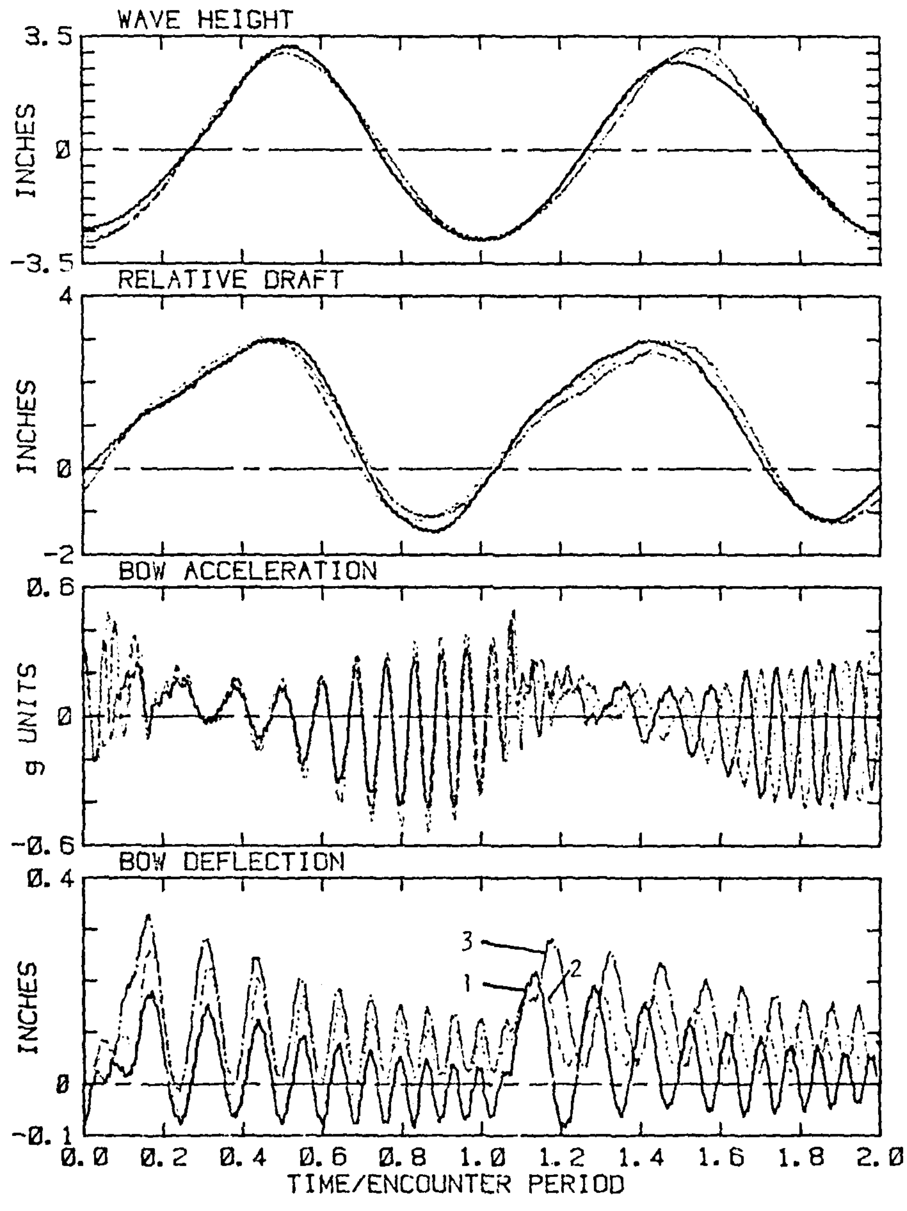


FIGURE 9.3 WAVE ELEVATION, KNUCKLE DRAFT, BOW ACCELERATION, AND BOW DEFLECTION, RUN 21.
MODEL SPEED ZERO, ENCOUNTER PERIOD 1.31 SECONDS, WAVE HEIGHT 5.67 INCHES

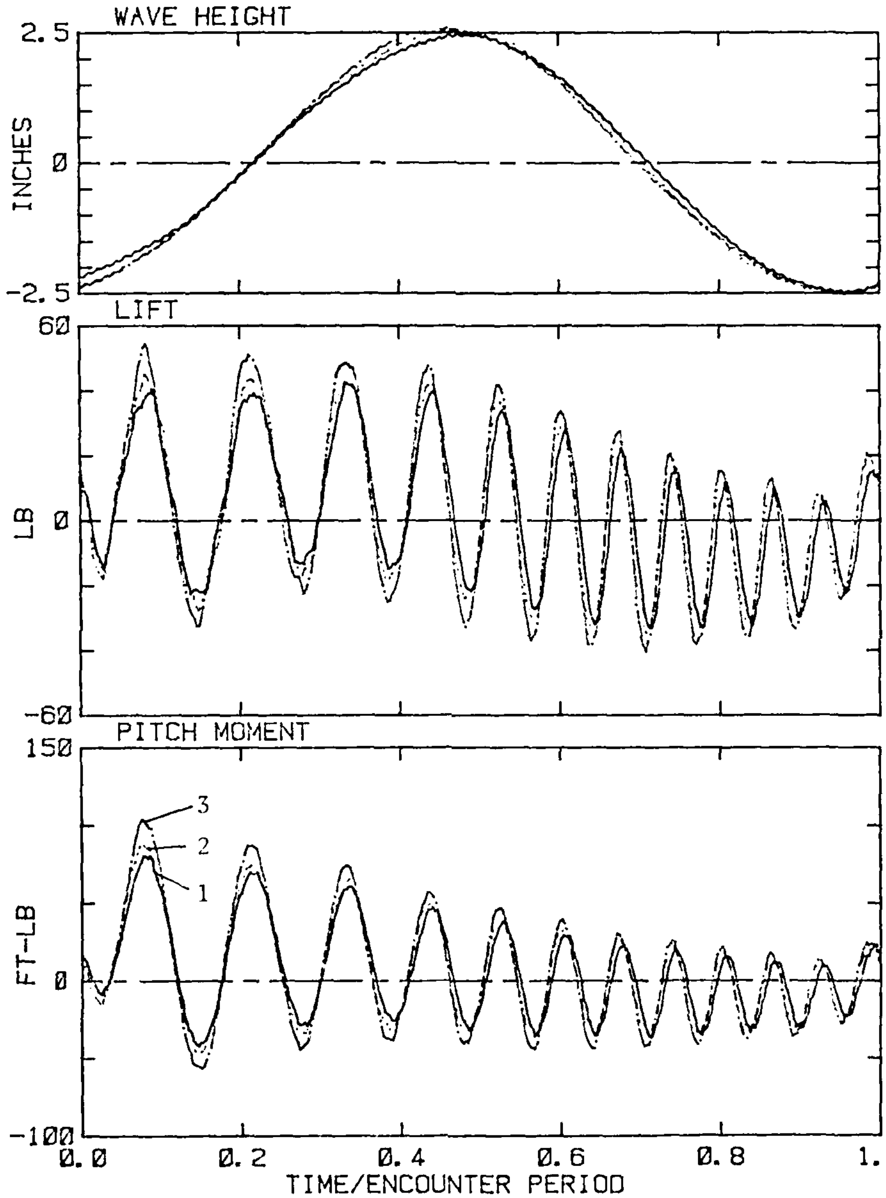


FIGURE 10.1 WAVE ELEVATION, SHEAR AND BENDING MOMENT, RUN 22 MODEL SPEED ZERO, ENCOUNTER PERIOD 1.39 SECONDS, WAVE HEIGHT 5.15 INCHES

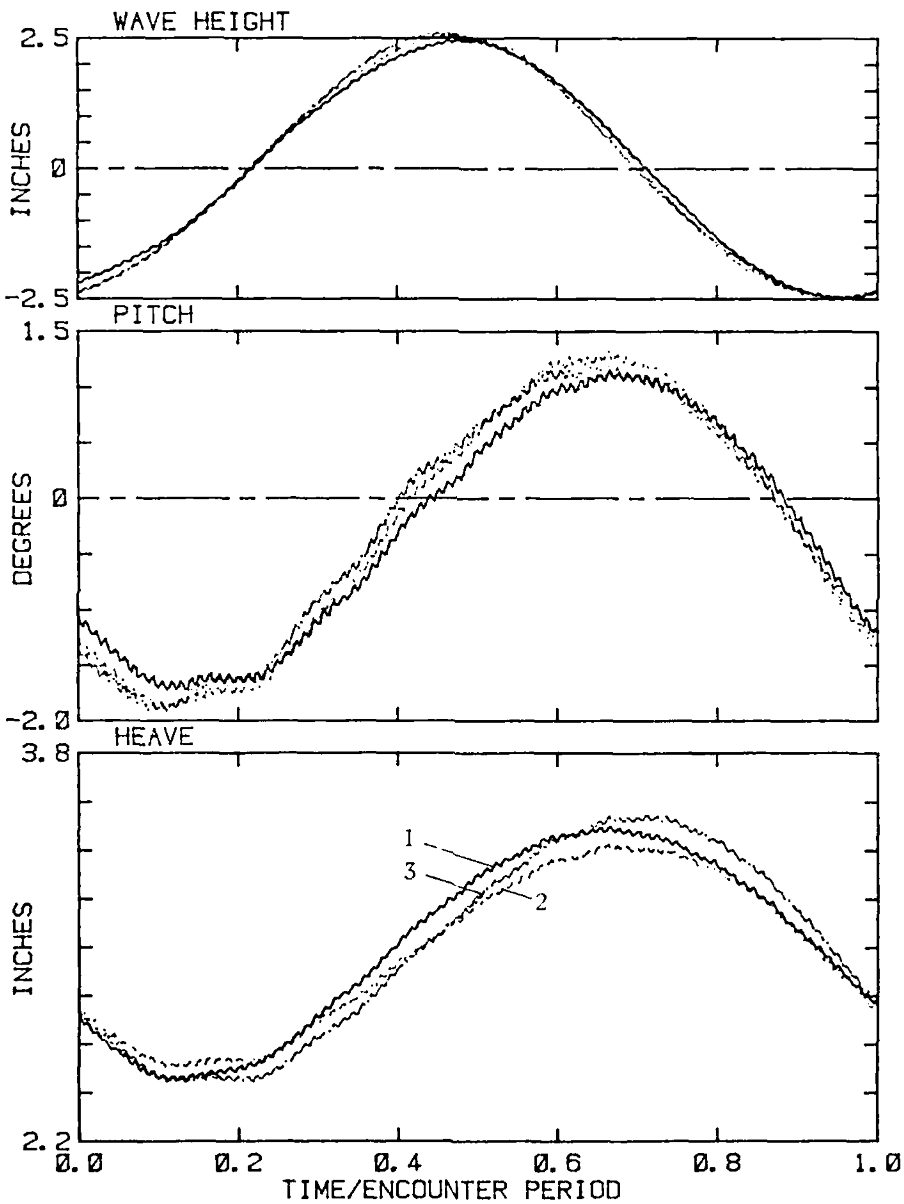


FIGURE 10.2 WAVE ELEVATION, PITCH AND HEAVE, RUN 22
MODEL SPEED ZERO, ENCOUNTER PERIOD 1.39 SECONDS
WAVE HEIGHT 5.15 INCHES

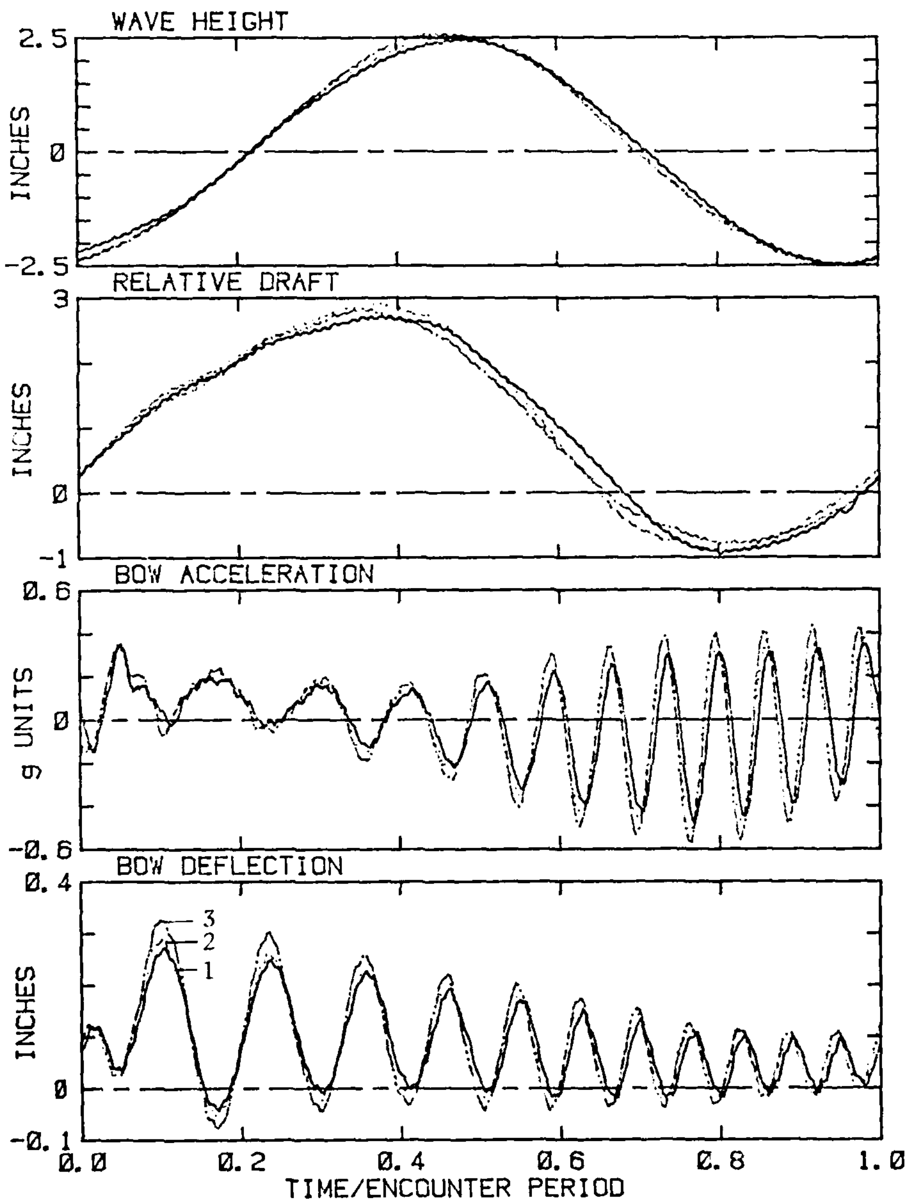


FIGURE 10.3 WAVE ELEVATION, KNUCKLE DRAFT, BOW ACCELERATION AND BOW DEFLECTION, RUN 22
MODEL SPEED ZERO, ENCOUNTER PERIOD 1.39 SECONDS, WAVE HEIGHT 5.15 INCHES

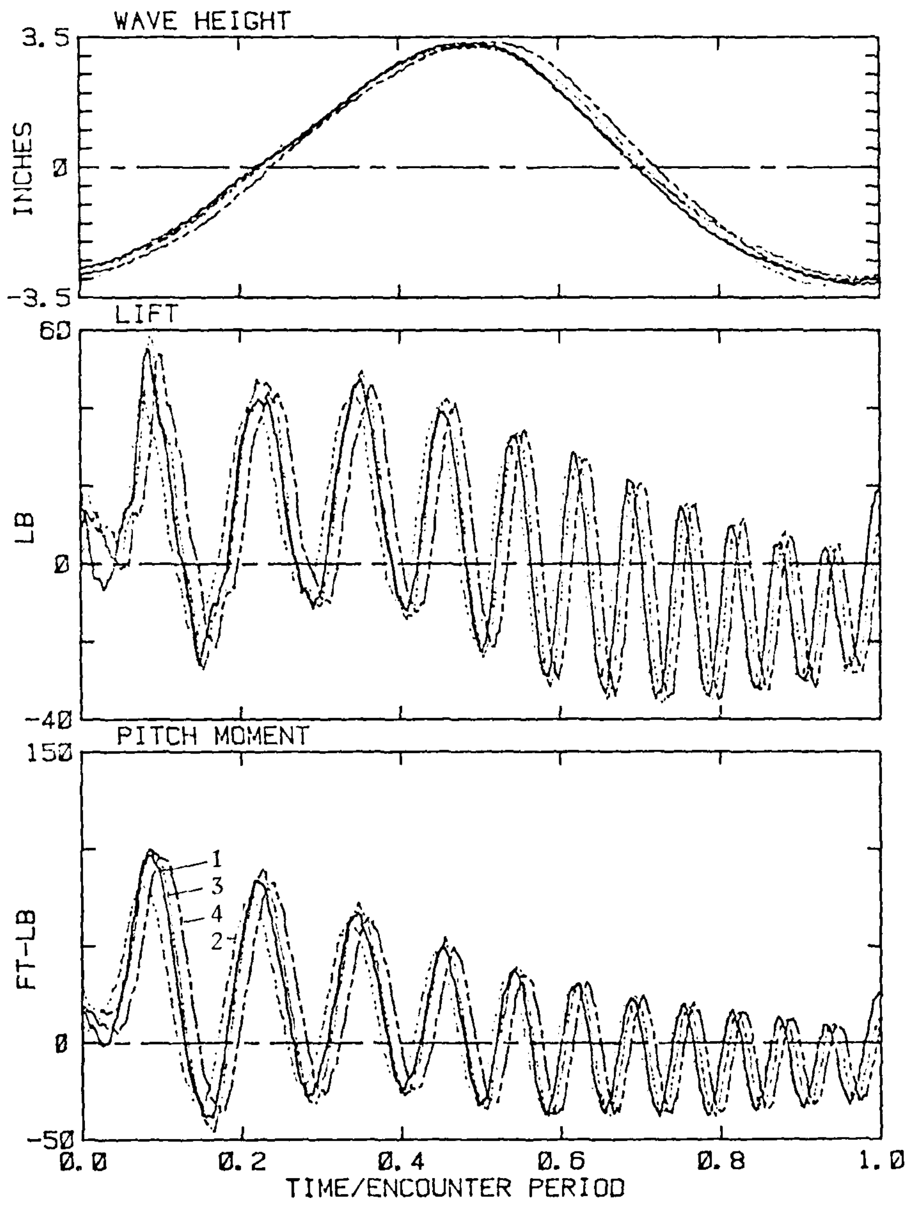


FIGURE 11.1 WAVE ELEVATION, SHEAR AND BENDING MOMENT, RUN 23 MODEL SPEED ZERO, ENCOUNTER PERIOD 1.41 SECONDS, WAVE HEIGHT 6.24 INCHES

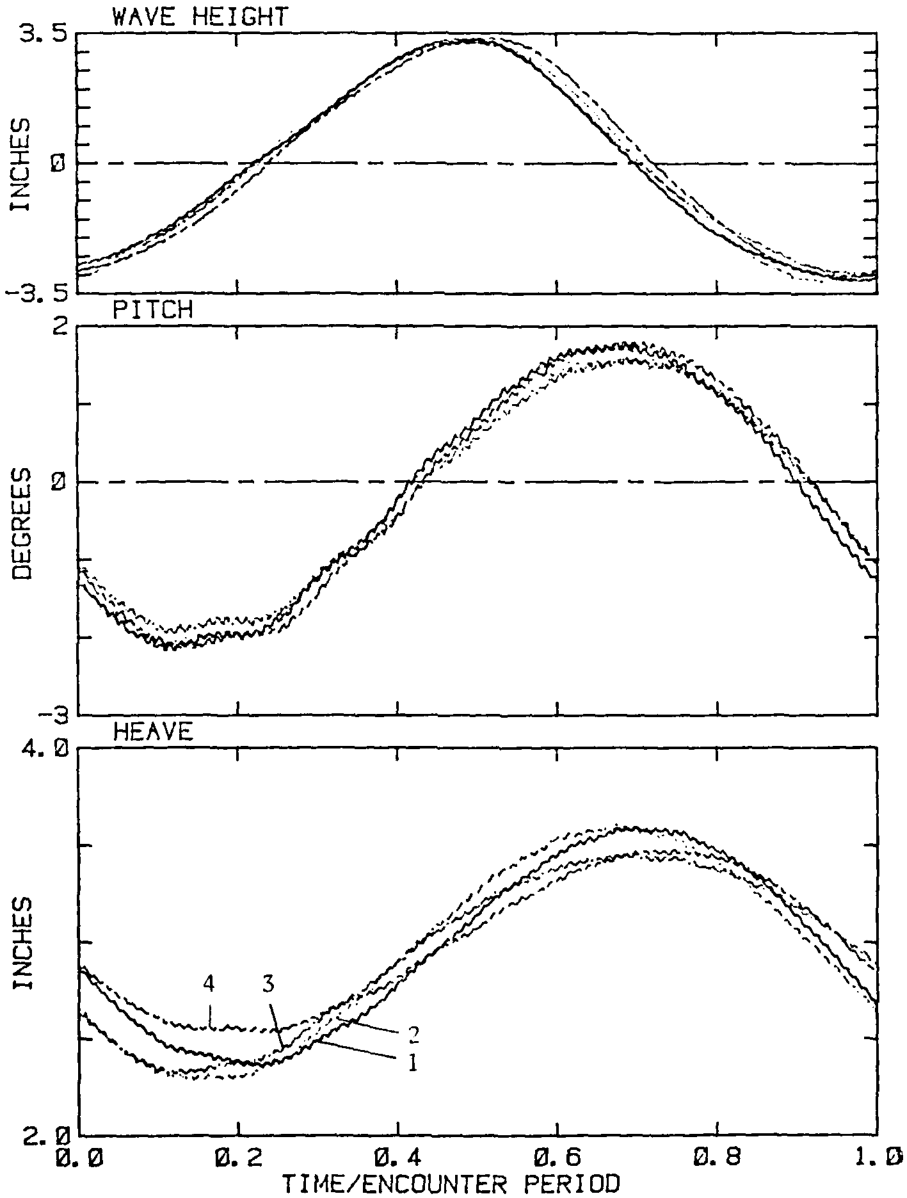


FIGURE 11.2 WAVE ELEVATION, PITCH AND HEAVE, RUN 23, MODEL SPEED ZERO, ENCOUNTER PERIOD 1.41 SECONDS, WAVE HEIGHT 6.24 INCHES

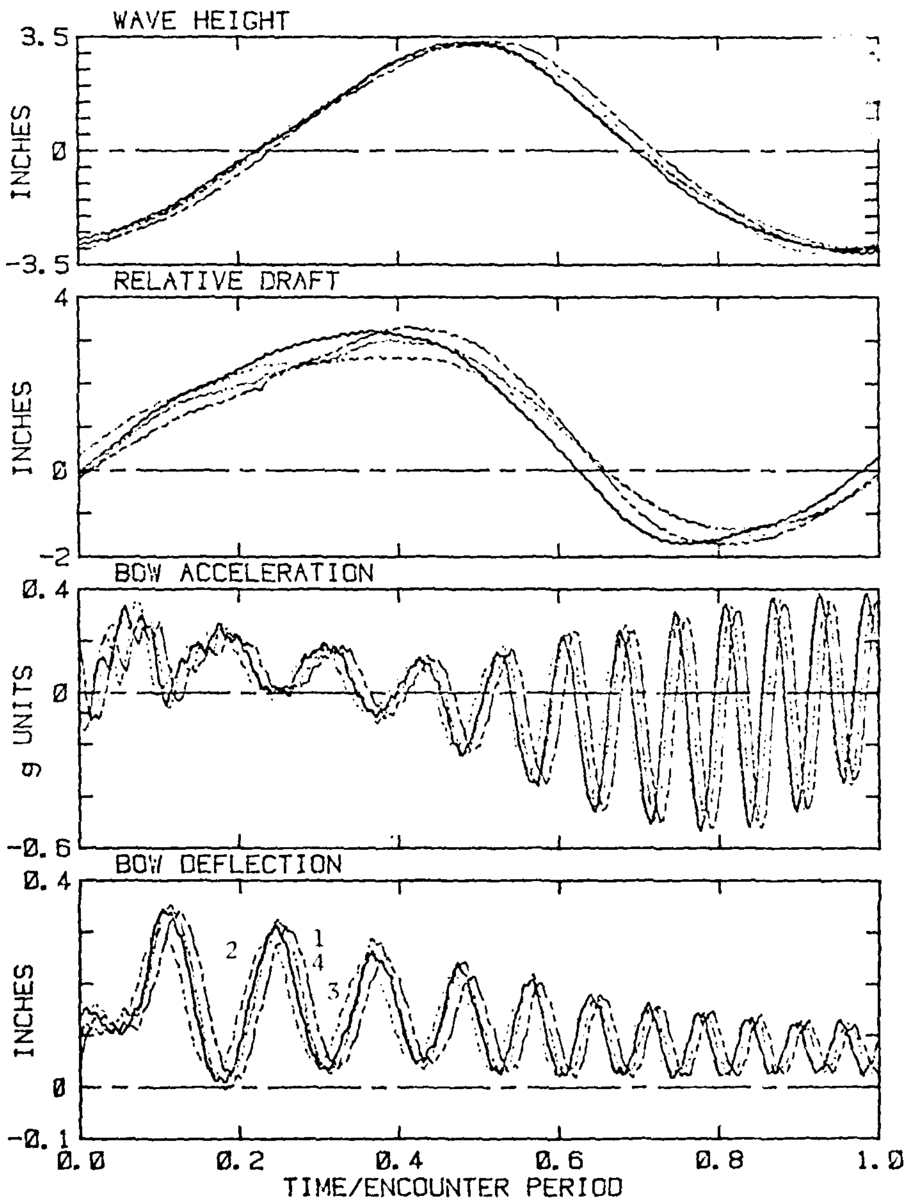


FIGURE 11.3 WAVE ELEVATION, KNUCKLE DRAFT, BOW ACCELERATION AND BOW DISPLACEMENT, RUN 23
MODEL SPEED ZERO, ENCOUNTER PERIOD 1.41 SECONDS, WAVE HEIGHT 6.24 INCHES

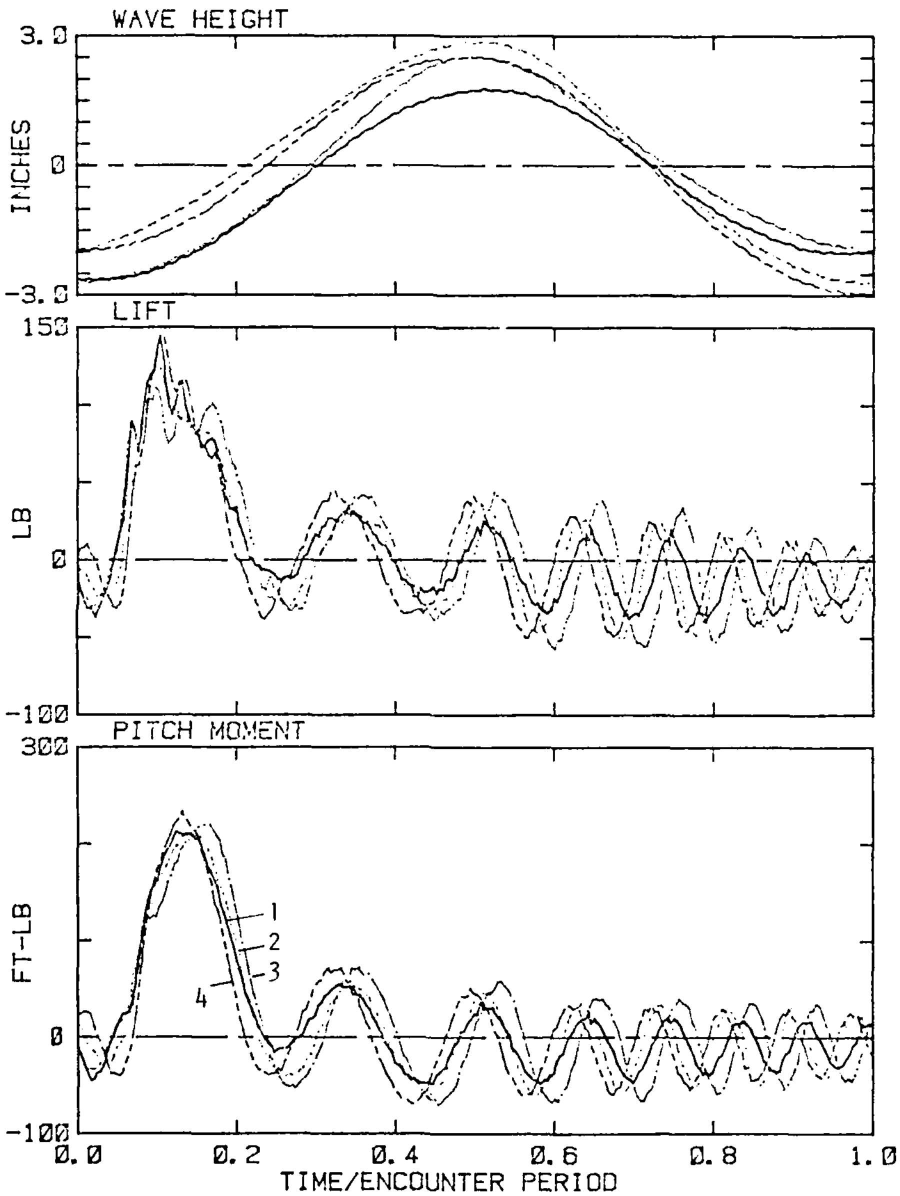


FIGURE 12.1 WAVE ELEVATION, SHEAR AND BENDING MOMENT, RUN 25. MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.00 SECONDS, WAVE HEIGHT 5.15 INCHES

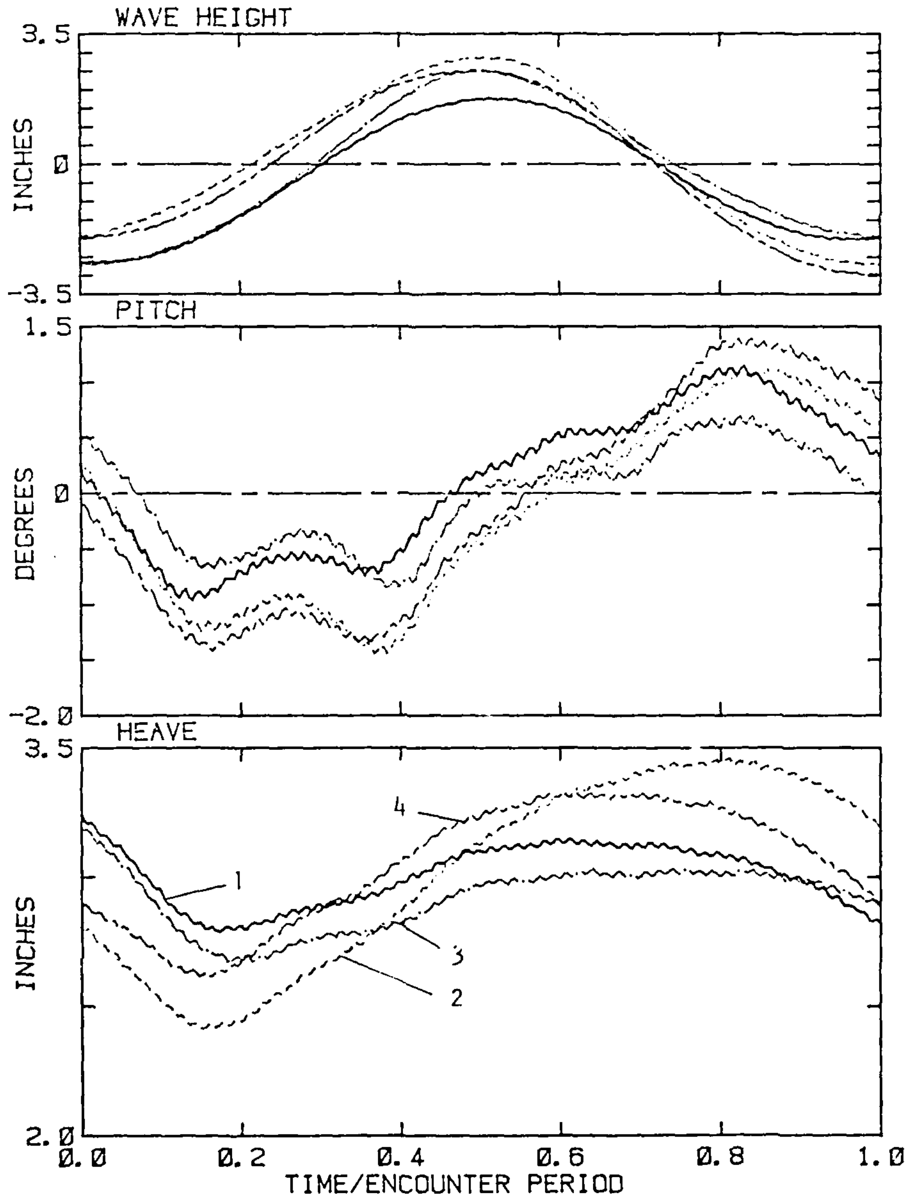


FIGURE 12.2 WAVE ELEVATION, PITCH AND HEAVE, RUN 25
MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.00 SECONDS,
WAVE HEIGHT 5.15 INCHES

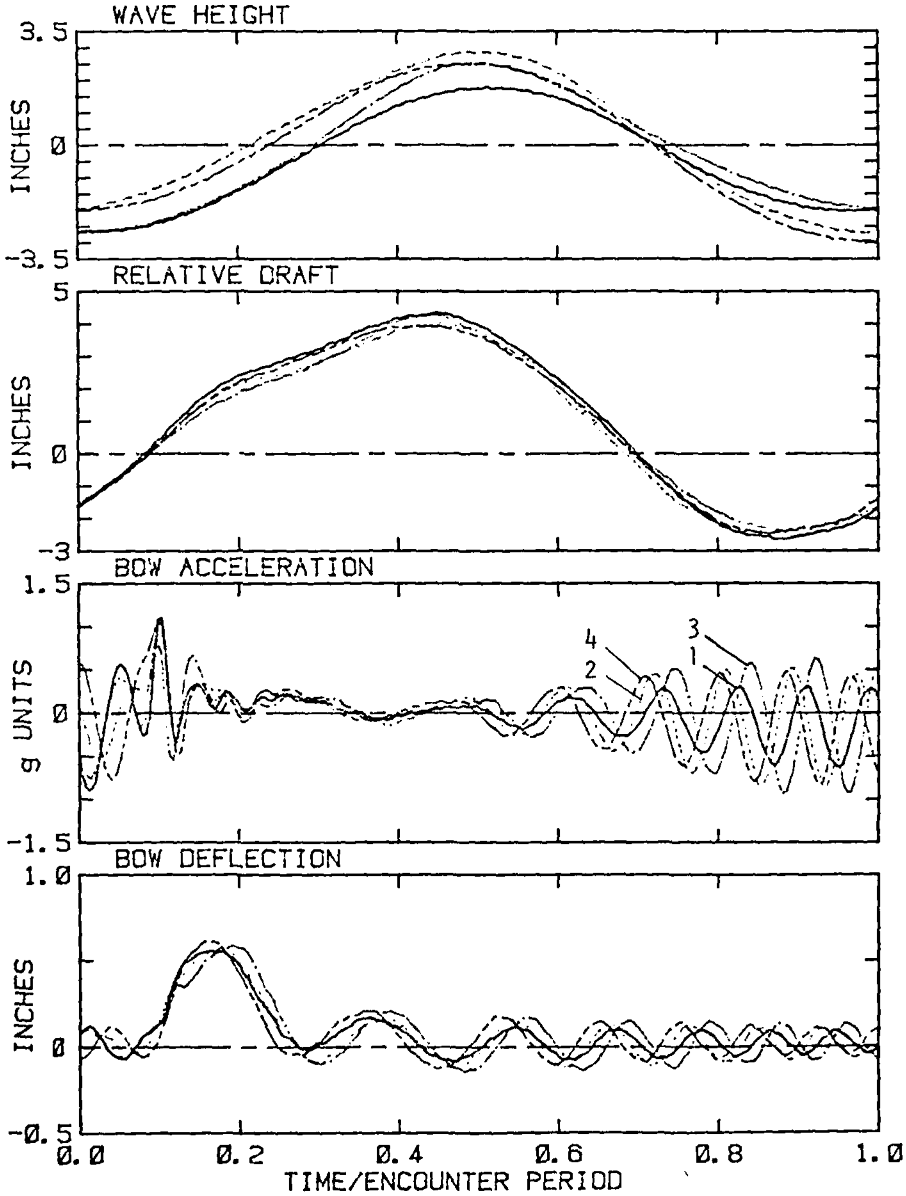


FIGURE 12.3 WAVE ELEVATION, KNUCKLE DRAFT, BOW ACCELERATION AND BOW DISPLACEMENT, RUN 25
MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.00 SECONDS, WAVE HEIGHT 5.15 INCHES

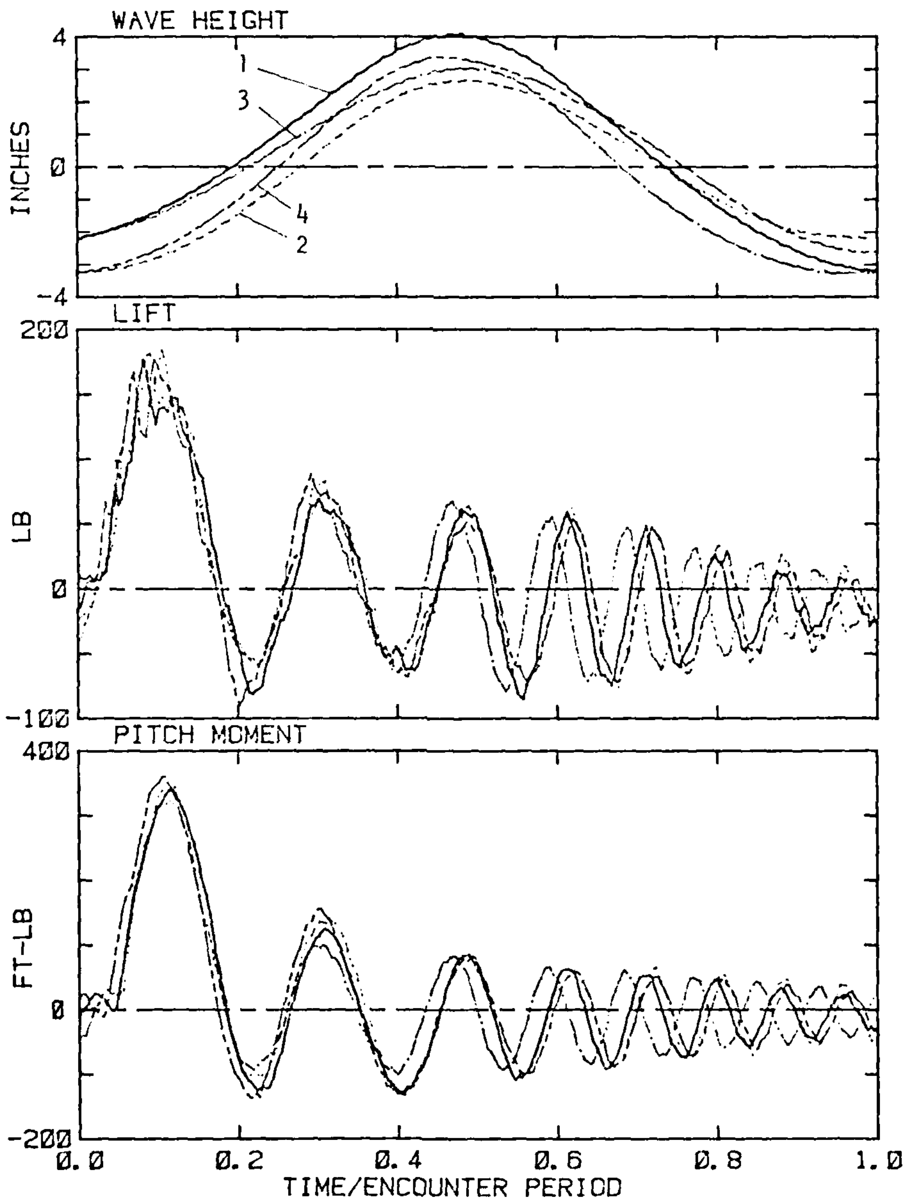


FIGURE 13.1 WAVE ELEVATION, SHEAR AND BENDING MOMENT, RUN 24. MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.03 SECONDS, WAVE HEIGHT 6.24 INCHES

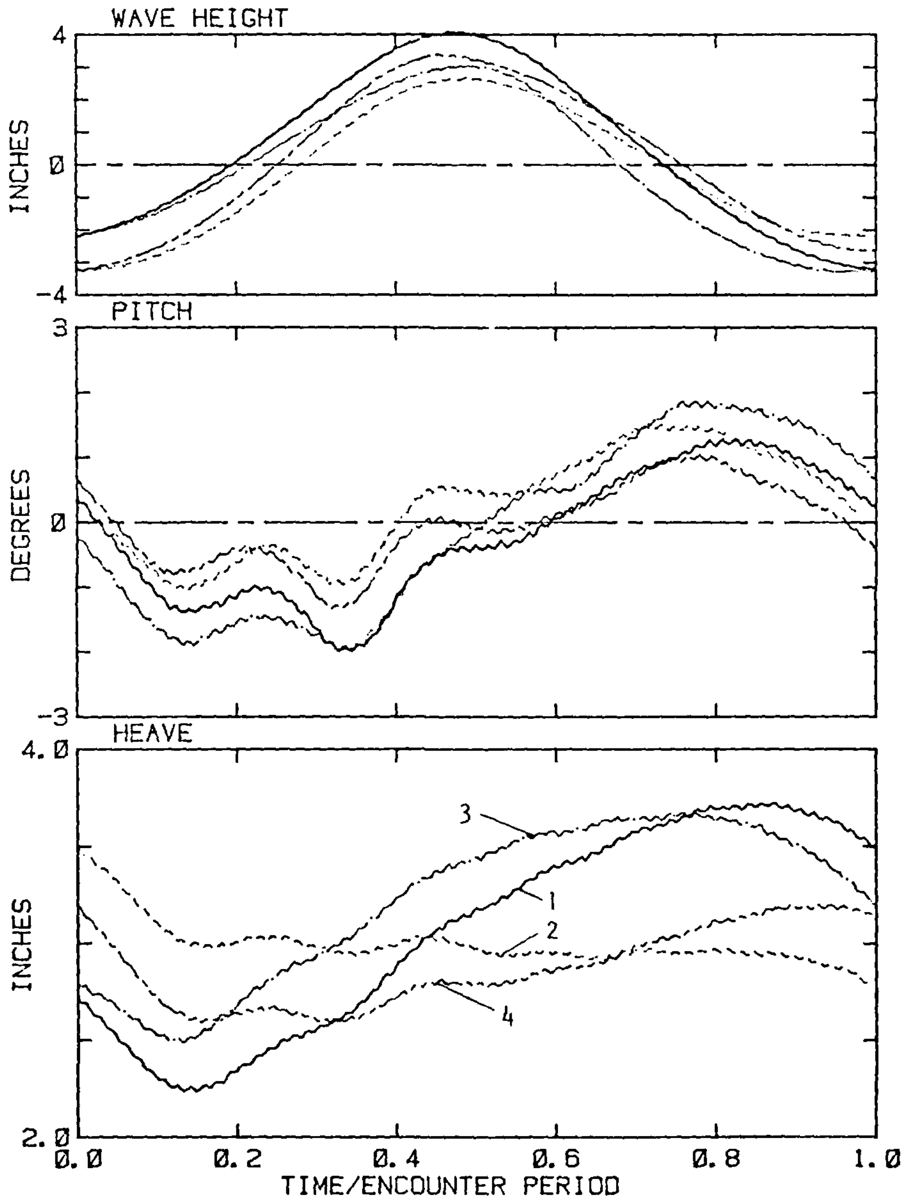


FIGURE 13.2 WAVE ELEVATION, PITCH AND HEAVE, RUN 24. MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.03 SECONDS, WAVE HEIGHT 6.24 INCHES

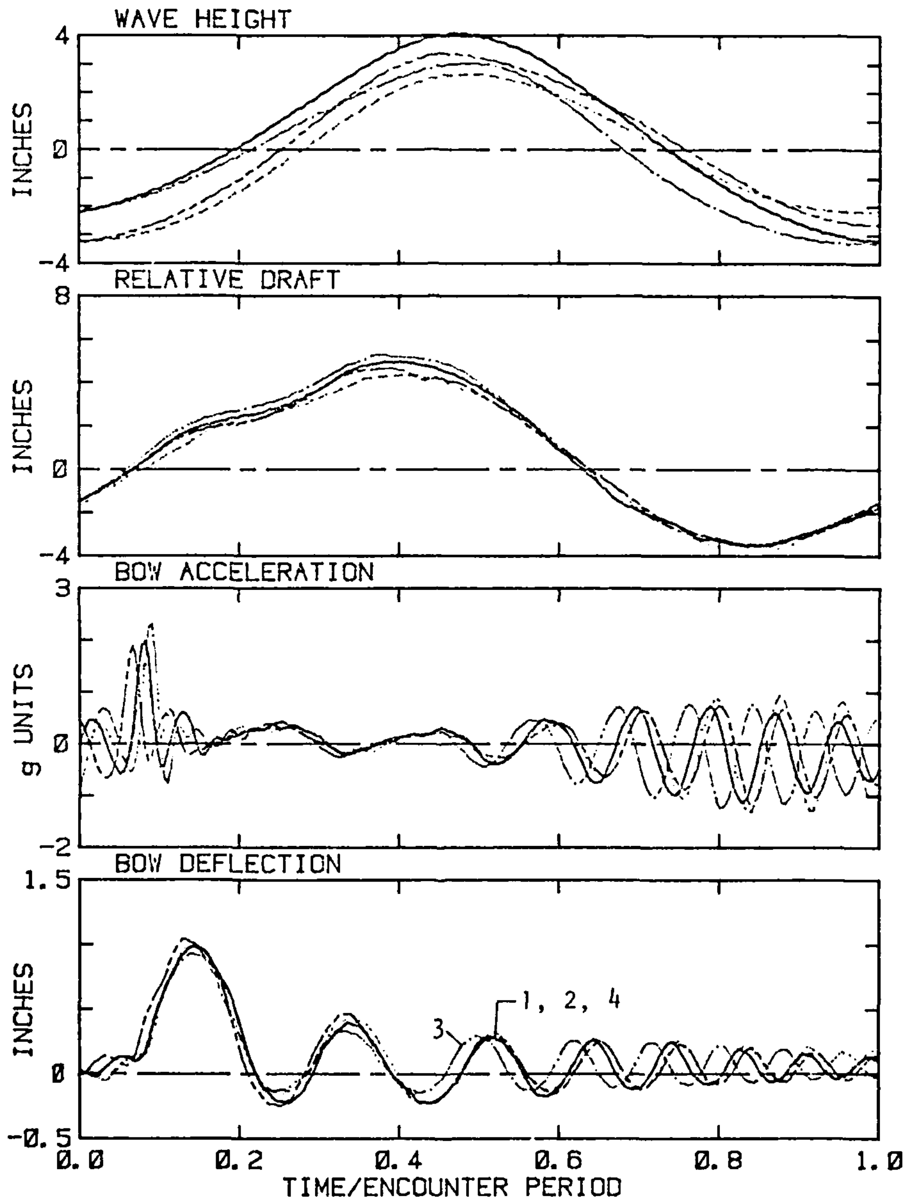


FIGURE 13.3 WAVE ELEVATION, KNUCKLE DRAFT, BOW ACCELERATION AND BOW DISPLACEMENT, RUN 24
MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.03 SECONDS, WAVE HEIGHT 6.24 INCHES

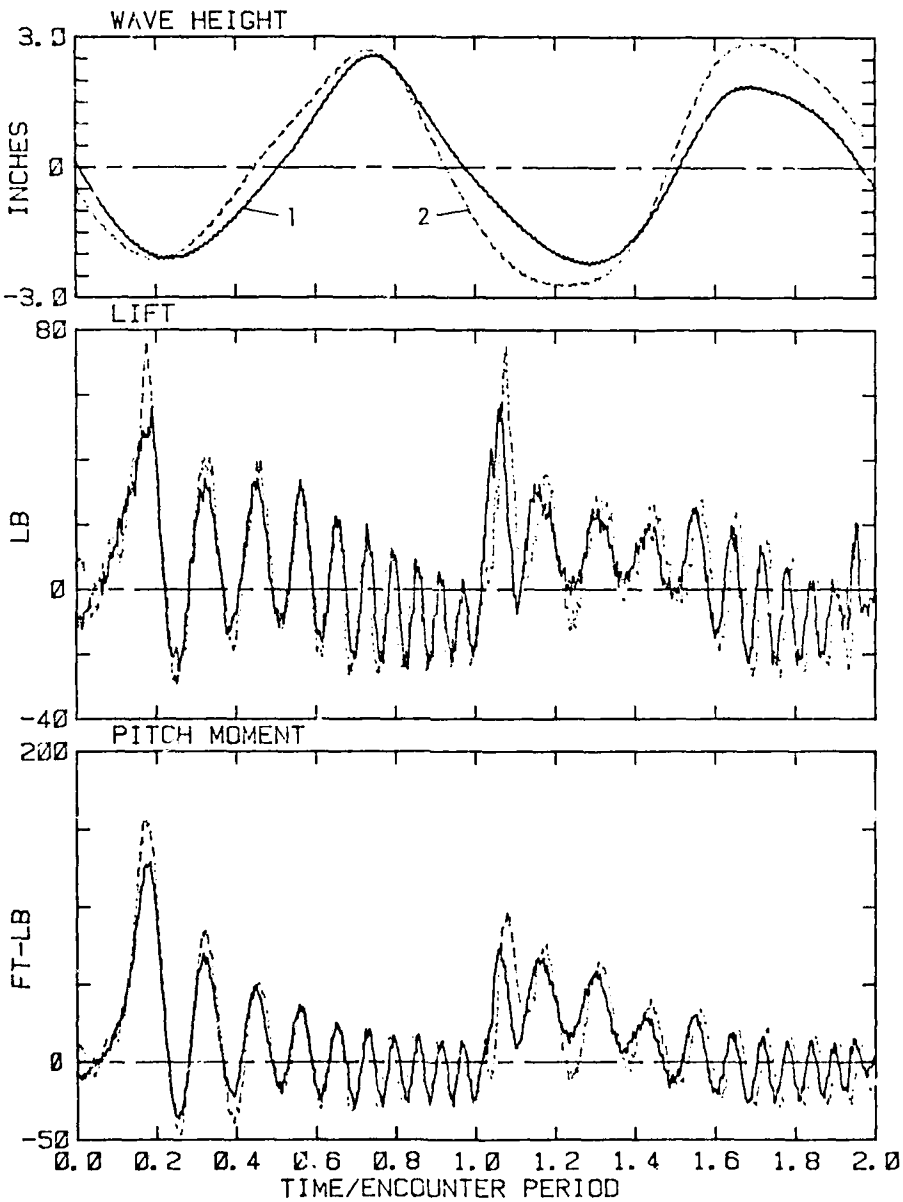


FIGURE 14.1 WAVE ELEVATION, SHEAR AND BENDING MOMENT, RUN 26 MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.39 SECONDS, WAVE HEIGHT 4.82 INCHES

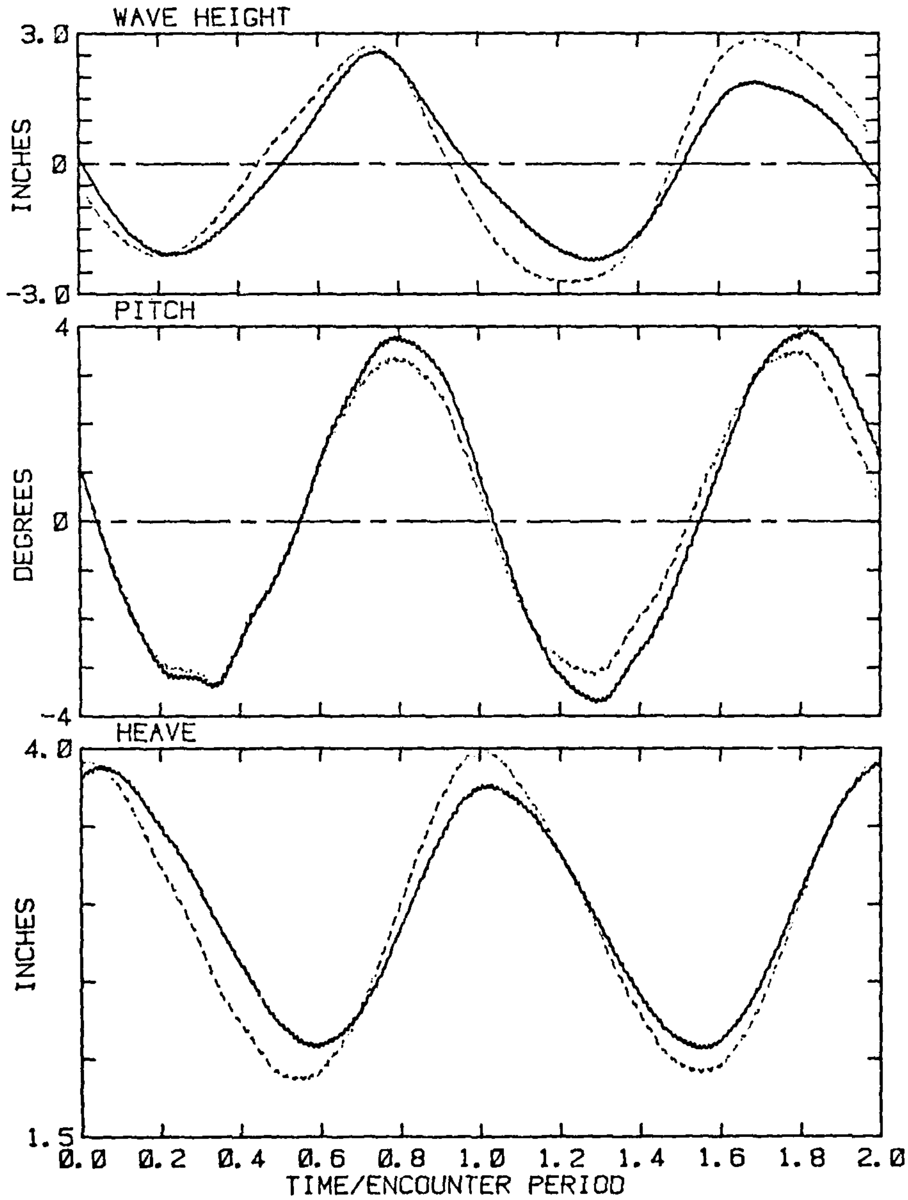


FIGURE 14.2 WAVE ELEVATION, PITCH AND HEAVE, RUN 26
MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.39 SECONDS,
WAVE HEIGHT 4.82 INCHES

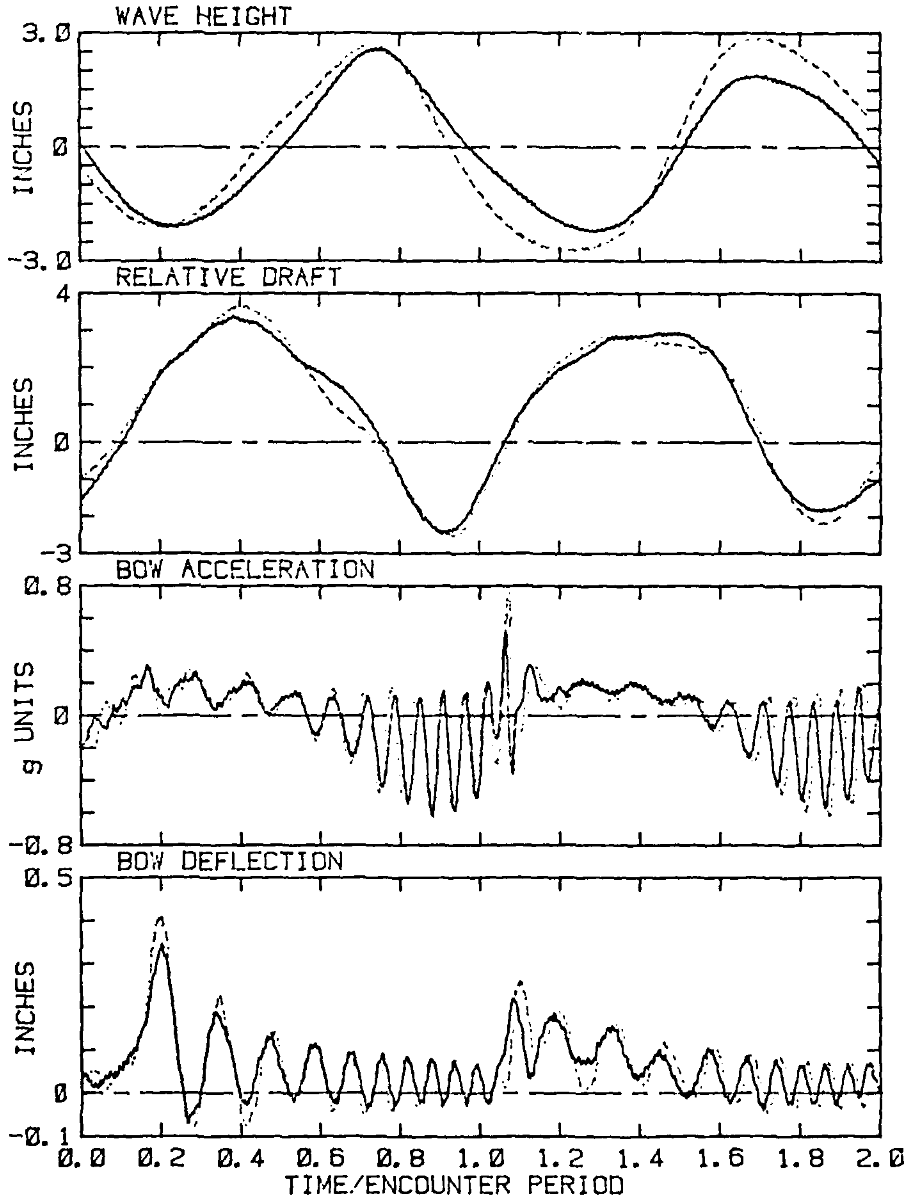


FIGURE 14.3 WAVE ELEVATION, KNUCKLE DRAFT, BOW ACCELERATION AND BOW DISPLACEMENT, RUN 26
MODEL SPEED 2.7 fps, ENCOUNTER PERIOD 1.39 SECONDS, WAVE HEIGHT 4.82 INCHES

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